



# Proceedings

ASPE 2011 Spring Topical Meeting

**Structured and Freeform Surfaces**

**March 2011**

American Society for

**Precision Engineering**

P.O. Box 10826, Raleigh, NC 27605-0826  
(919) 839-8444 | Fax (919) 839-8039





**Proceedings of:**

# **Structured and Freeform Surfaces**

## **2011 Spring Topical Meeting**

March 6 to 8, 2011

University of North Carolina at Charlotte Campus  
Charlotte, North Carolina

The American Society for Precision Engineering (ASPE) is a multidisciplinary professional and technical society concerned with research and development, design, manufacture and measurement of high accuracy components and systems. ASPE activities encompass relevant aspects of mechanical, electronic, optical and production engineering, physics, chemistry, and computer and materials science. Membership is open to anyone interested in any aspect of precision engineering.

Founded in 1986, ASPE provides a new focus for a diverse but important community. Other professional organizations have covered aspects of precision engineering, always as a sideline to their principal goals. ASPE is based on the core of generic concepts necessary to achieve precision in any application; independent of discipline, ASPE intends to be the focus for precision technology, and to represent all facets from research to application.

ASPE – The American Society for Precision Engineering  
301 Glenwood Avenue, Suite 205, Raleigh, NC 27603  
P.O. Box 10826, Raleigh, NC 27605  
Telephone: (919) 839-8444 Fax (919) 839-8039  
Web site: <http://www.aspe.net>

# Preface

This book comprises the proceedings of the 2011 Spring Topical Meeting. The contributions reflect the authors' opinions and are published as presented to ASPE, without change. Their inclusion in this publication does not necessarily constitute endorsement by the ASPE, or its editorial staff.

Individual readers of this book and nonprofit libraries acting for them are permitted to make fair use of the material contained in this book to be used in teaching or research; provided they copy said paper in total, as written by the author. Permission is granted to quote excerpts from the scientific or technical works in this book with proper acknowledgment of the source to include: The author's name, the book name, and the ASPE tag line. Reproduction of figures and tables is likewise permitted from the contents of this book, provided that the same acknowledgment of the same source and content is permitted.

Any other type reproduction, systematic copying or multiple reproduction of any material in this book is expressly prohibited except with the written permission of the ASPE editorial staff, addressed to the Society's headquarters.

ISBN 978-1-887706-57-5

2011

American Society for Precision Engineering  
301 Glenwood Avenue, Suite 205  
Raleigh, NC 27603

Printed in the United States of America

# 2011 Spring Topical Meeting

## Contents

|                                     |         |
|-------------------------------------|---------|
| Preface .....                       | ii      |
| Contents .....                      | iii     |
| Program.....                        | iv      |
| Foreword.....                       | v       |
| Technical Paper Index .....         | vi-ix   |
| Technical Papers .....              | 3-167   |
| Author Index .....                  | 169-170 |
| Sustaining Corporate Sponsors ..... | 171     |
| Corporate Sponsors .....            | 172     |

# 2011 Spring Topical Meeting

## Meeting Schedule

|       | Sunday, March 6                        |       | Monday, March 7                         |               | Tuesday, March 8                       |
|-------|----------------------------------------|-------|-----------------------------------------|---------------|----------------------------------------|
| 7:00  | Registration and Continental Breakfast | 7:00  | Registration and Continental Breakfast  |               |                                        |
| 8:00  | TUTORIAL I                             | 8:15  | Welcome & Opening Remarks               | 7:30          | Registration and Continental Breakfast |
| 9:45  |                                        | 8:30  | TECHNICAL SESSION I                     | 8:30<br>10:00 | TECHNICAL SESSION V                    |
|       | Coffee Break                           |       | Coffee Break                            |               | Coffee Break                           |
| 10:15 | TUTORIAL I                             | 10:30 | TECHNICAL SESSION II                    | 10:30         | TECHNICAL SESSION VI                   |
| 12:00 |                                        | 12:00 |                                         | 12:00         |                                        |
|       | Box Lunch                              |       | Lunch                                   |               | Lunch                                  |
| 1:00  | TUTORIAL II                            | 1:00  | TECHNICAL SESSION III                   | 1:00          | TECHNICAL SESSION VII                  |
| 2:45  |                                        | 2:30  |                                         | 2:30          |                                        |
|       | Break                                  |       | Break                                   |               | Break                                  |
| 3:15  | TUTORIAL II                            | 3:00  | TECHNICAL SESSION IV<br>KEYNOTE SESSION | 3:00          | TECHNICAL SESSION VIII                 |
| 5:00  |                                        | 4:00  |                                         | 4:30          |                                        |
|       |                                        |       | POSTER SESSION<br>AND RECEPTION         |               |                                        |
|       |                                        | 5:30  |                                         |               |                                        |
|       |                                        | 6:45  | LAB TOUR                                |               |                                        |
|       |                                        | 7:00  | DINNER AT<br>UNIVERSITY HILTON<br>HOTEL |               |                                        |
|       |                                        | 9:00  |                                         |               |                                        |

# Foreword

The ASPE Spring Topical Meeting on “Structured and Freeform Surfaces” addresses the technical challenges of both fabrication and metrology in this rapidly growing field.

The manufacture of structured and freeform surfaces are driving advances in cell phones, touch screen displays, automobile head and tail lamps, military night vision systems, hip replacement implants, contact lenses and other medical, energy and computing technologies.

This topic has tremendous interest worldwide, and to that end we are jointly presenting this meeting with **euspen**, our European counterpart, to gather the global experts in this exciting field.

This conference is intended to promote a broader understanding of the principles and techniques applicable structured and freeform surfaces, to highlight the challenges and achievements unique to our field, to bring together specialists and practitioners from industry, government, and academia for the exchange of ideas, and to identify topics for further research. The conference schedule will include significant unstructured time to allow for technical and social interactions.

## 2011 Spring Topical Meeting Program Committee:

### Meeting Co-Chairmen:

**Matthew A. Davies**

University of North Carolina at Charlotte

**Richard K. Leach**

National Physical Laboratory, UK

### Scientific Committee:

Thomas A. Dow, North Carolina State University

Dan E. Luttrell, Moore Tool Company

Jeffrey W. Roblee, AMETEK Precitech, Inc.

Paul Shore, Cranfield University

Christian Wenzel, Fraunhofer Institute for Production Technology IPT

# Technical Sessions

## Welcome and Opening Remarks

Monday, March 7, 2011, 8:15 AM - 8:30 AM

## Session I

### New Methods in Optical Fabrication

Monday, March 7, 2011, 8:30 AM - 10:00 AM

1. **A New Generation of Optical Systems with  $\varphi$ -polynomial Surfaces**  
Fuerschbach, K. H.; Rolland, J. P. (University of Rochester); and  
Thompson, K. P. (Synopsis Inc.) . . . . . 3
2. **Anamorphic Imaging with Three Mirrors: Surface Forms**  
Howard, J. M. (NASA/Goddard Space Flight Center) . . . . . 8
3. **Structured Surfaces for Biomimetic Micro-optical Systems\***  
Cannistra, A. T.; Dutterer, B. S.; Davies, M. A.; Suleski, T. J. (University of  
North Carolina at Charlotte) . . . . . 10
4. **A New Way to Mold Lenses with Freeform and Structured Surfaces**  
Plummer, W. T. (WTP Optics, Inc.) . . . . . 11

## Session II

### Machining of Freeform & Structured Optics I

Monday, March 7, 2011, 10:30 AM - 12:00 PM

1. **Freeform Surface Fabrication in Cylindrical Coordinates**  
Garrard, K. P.; Sohn, A.; Dow, T. A. (North Carolina State University) . . . . . 13
2. **Freeform Manufacturing of a Microoptical Lens Array on a Curved Substrate**  
Scheiding, S.; Gebhardt, A.; Risse, S.; Eberhardt, R.; Tünnermann, A. (Fraunhofer Institute  
for Applied Optics and Precision Engineering Jena); and Yi, A. Y.; Li, L. (The Ohio  
State University) . . . . . 19
3. **Precision Machining of Non-axisymmetric Aspheric Glass Lens Mold with Micro  
Fresnel Structures**  
Yamamoto, S.; Nakamoto, K.; Ishida, T.; Takeuchi, Y. (Osaka University); and Hirano, M.  
(JTEKT Corporation) . . . . . 24
4. **Diamond Micro Chiseling of Large-scale Retroreflective Arrays**  
Brinksmeier, E.; Schönemann, L.; Gläbe, R.; (Bremen University); and Weingärtner, S.  
(IMOS Gubela GmbH) . . . . . 29

*\*No extended abstract available at press time*

## Session III

### Metrology for Freeform Optics

Monday, March 7, 2011, 1:00 PM - 2:30 PM

1. **Metrology with a Non-contact Probe for Manufacturing Freeform Optics**  
DeFisher, S.; Lambropoulos, T.; Bambrick, S. T.; Shafrir, S. N. (OptiPro Systems) . . . . . 34
2. **Four-axis Spherical Geometry Measurement of Freeform Surfaces – Polaris 3D**  
Sohn, A.; Garrard, K. P.; Dow, T. A. (North Carolina State University) . . . . . 38
3. **Slope Measuring Metrology for Precision Freeform Surfaces**  
Parks, R. E.; Su, P.; Su, T.; Park, W. H.; Dominguez, M.; Wang, L.; Zhu, G.;  
Butel, G.; Lu, S.-H.; Wang, Y.; Zhou, P.; Burge, J. H. (University of Arizona) and  
Zobrist, T. (Steward Observatory Mirror Lab). . . . . 43
4. **Adaptive Inspection of Free-form Surfaces in Coordinate Metrology**  
Ascione, R. (Universita degli Studi di Cassino); Moroni, G.; Petrò, S. (Politecnico di Milano);  
and Romano, D. (University of Cagliari) . . . . . 49

## Session IV

### Keynote Session

Monday, March 7, 2011, 3:00 PM - 4:00 PM

1. **Microstructured Surfaces\*\***  
Walker, N. (Microsharp Corporation Ltd.)
- 2 **Precision Optics: Mid-Spatial Frequency Matters\*\***  
Hull, T.; Carrigan, K. (Tinsley Laboratories, Inc.)

## Poster Session and Reception

Monday, March 7, 2011, 4:00 PM - 5:30 PM

1. **Creating Functional Surface Structures by Milling Using Self-excited Tool Vibrations**  
Biermann, D.; Surmann, T.; Odendahl, S.; Steiner, M.; Hense, R.; Rausch, S.  
(Technical University of Dortmund) . . . . . 55
2. **Nano/Micro Machining Using Multi-arrayed Tool for Nano/Micro Surface Patterning**  
Choi, S.; Lee, S.-M.; Lu, H.; Lee, D. W. (Pusan National University); and Park, J.-K.  
(Korea Institute of Machinery & Materials (KIMM)) . . . . . 59
3. **Geometrical Analysis of Surface Finish by Ultrasonic Vibration Assisted Grinding**  
Ismail, M. F. (Universiti Teknologi MARA); and Yanagi, K.; Isobe, H.; (Nagaoka  
University of Technology). . . . . 63
4. **Data Acquisition and Analysis of Multi Wave Standards**  
Jusko, O. E.; Bosse, H.; Donatelli, G.; Härtig, F.; Kniel, K. (Physikalisch Technische  
Bundesanstalt); and Arenhart, F. A.; de C. Porath, M. (CERTI Foundation). . . . . 68
5. **Analysis of Brightness Enhancement in a Smart Textured LGP (Light Guide Panel)  
with a Short Pulsed Laser \*\***  
Kim, K.; Suh, J.; Lee, J.; Park, J.-K. (Korea Institute of Machinery & Materials (KIMM))

*\*\*No abstract available*

|                                                                                                                                                                                                                                                                                                                                     |     |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>6. The Importance of Spindle Balancing for the Machining of Freeform Optics</b><br>Knapp, B. R.; Arneson, D. A.; Oss, D.; Liebers, M. J.; (Professional Instruments Company, Inc.);<br>Vallance, R. R. (The George Washington University); and Marsh, E. R. (The Pennsylvania<br>State University) . . . . .                     | 74  |
| <b>7. Microgrinding with Microwheels Shaped by Micro Electro-discharge Machining</b><br>Morgan, C. J.; Huber, J. (AMT nano, LLC); and Stephens, S. (University of Kentucky) . . . . .                                                                                                                                               | 79  |
| <b>8. Characterization of Structured Surfaces Using Multi-parameter Based Masking<br/>and Segmentation Approach</b><br>Ramasamy, S. K.; Boudreau, B. D.; Raja, J. (University of North Carolina at Charlotte) . . . . .                                                                                                             | 82  |
| <b>9. Five Axis Polishing of Freeform Precision Optics*</b><br>Shafir, S. N.; Fess, E.; Cannarozzo, V.; Bambrick, S.; Tierson, J. (OptiPro Systems) . . . . .                                                                                                                                                                       | 87  |
| <b>10. Direct Engraving of 20-<math>\mu</math>m Wide Patterns Into a Ni-Plated Roll Using Fiber Laser</b><br>Sohn, H.; Suh, J.; Park, J.-K. (Korea Institute of Machinery & Materials (KIMM)) . . . . .                                                                                                                             | 88  |
| <b>11. An Experimental Study on Real-time Monitoring of Grinding Wheel Surface Shape<br/>and Topography with Ultra-high Frequency Laser Displacement Sensor</b><br>Stanco, M. R.; Bryant, L. A.; Li, Z. C. (North Carolina Agricultural & Technical State<br>University); and Vergara, J. (Keyence Corporation of America). . . . . | 91  |
| <b>12. Geometrical and Material Modification of Stainless Steel and Aluminum<br/>Alloy Surfaces Induced by Fine Burnishing Process</b><br>Tanaka, H.; Yanagi, K. (Nagaoka University of Technology). . . . .                                                                                                                        | 96  |
| <b>13. Engineered Surfaces Characterization Methodology</b><br>Verma, R.; Raja, J. (University of North Carolina at Charlotte) . . . . .                                                                                                                                                                                            | 101 |

## Session V

### Machining of Freeform Optics & Structures II

Tuesday, March 8, 2011, 8:30 AM - 10:00 AM

|                                                                                                                                                                                                         |     |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>1. High Speed Milling of an Alvarez Optic</b><br>Lineberger, J. L.; Dutterer, B. S.; Davies, M. A.; Smilie, P.; Suleski, T. J. (University of<br>North Carolina at Charlotte) . . . . .              | 105 |
| <b>2. X-C-Z Ultra-precision Micromilling</b><br>Davis, G. E.; Hedges, A. R. (II-VI Incorporated); and Roblee, J. W. (AMETEK - Precitech, Inc.) . . . . .                                                | 111 |
| <b>3. Feedback of Measurement Data for Corrective Machining of Freeform Surfaces</b><br>Brecher, C.; Wenzel, C.; Buß, C.; Clemens, J. (Fraunhofer Institute for<br>Production Technology IPT) . . . . . | 117 |
| <b>4. Micromilling of Bionic Structures</b><br>Biermann, D.; Krebs, E.; Schlenker, J. (Technical University of Dortmund) . . . . .                                                                      | 120 |

## Session VI

### Metrology – Small to Large

Tuesday, March 8, 2011, 10:30 AM - 12:00 PM

|                                                                                                                                                        |     |
|--------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>1. Measurements of Structured Surfaces – Can They Be Made Traceable? *</b><br>Leach, R. K.; Giusca, C. (National Physical Laboratory, UK) . . . . . | 126 |
|--------------------------------------------------------------------------------------------------------------------------------------------------------|-----|

*\*No extended abstract available at press time*



|                                                                                                                                                                                                                                                                                          |     |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>2. Multi-scale Structures for Influencing the Tribological Properties of Metallic Surfaces</b><br>Neugebauer, R.; Schubert, A.; Avila, M.; Sylla, D. (University of Technology Chemnitz);<br>and Schmidt, T. (Fraunhofer Institute of Machine Tools and Forming Technology) . . . . . | 127 |
| <b>3. Metrology of Aspheric and Freeform Lenses Based on Contour and Form</b><br>Beutler, A. (Mahr GmbH) . . . . .                                                                                                                                                                       | 133 |
| <b>4. Surface Form Measurements Combining Beam Propagation, Optical Scattering,<br/>and Photogrammetry</b><br>Bowes, K. E.; Mullany, B. A.; Morse, E. P.; Davies, A. D. (University of<br>North Carolina at Charlotte) . . . . .                                                         | 137 |

## Session VII

### Precision Fabrication

**Tuesday, March 8, 2011, 1:00 PM - 2:30 PM**

|                                                                                                                                                                                                    |     |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>1. Novel Use of a Traditional Machining Method for Generation of Large Scale<br/>Micro-structured Surfaces</b><br>Luttrell, D. E. (Moore Tool Company, Inc.) . . . . .                          | 143 |
| <b>2. Freeform Microstructured Stainless Steel Molds</b><br>Cannon, A. H.; Maguire, M.; King, W. P. (Hoowaki LLC) . . . . .                                                                        | 147 |
| <b>3. Injection Mold Process Optimization for Surface Microfeature Control</b><br>Dubey, M.; Mears, L. (Clemson University); and Cannon, A. H.; Hulseman, R. (Hoowaki LLC) . . . . .               | 150 |
| <b>4. Production and Measurement of Engineered Surfaces for Use in Inertial<br/>Confinement Fusion Research</b><br>Day, R. D.; Hatch, D. J.; Rivera, G. (Los Alamos National Laboratory) . . . . . | 156 |

## Session VIII

### Metrology for Biological Surfaces

**Tuesday, March 8, 2011, 3:00 PM - 4:30 PM**

|                                                                                                                                                                                                                          |     |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| <b>1. Characterizing Radii on the Tips of Biopsy Needles *</b><br>Gleason, M. A.; Brown, C. A. (Worcester Polytechnic Institute); and Moore, J. Z.;<br>Shih, A. J. (University of Michigan) . . . . .                    | 161 |
| <b>2. New Measurement Technique in Research and Development of<br/>Bioresorbable Implant Material</b><br>Scherer, S. (Alicona Imaging GmbH); and Fischerauer, S.; Weinberg, A. (Medical<br>University of Graz) . . . . . | 162 |
| <b>3. Metrological Characterization of Reptilian Skin for Green Tribo Surfaces *</b><br>Abdel-Aal, H. A.; El Mansori, M. (Arts et Metiers Paris Tech) . . . . .                                                          | 167 |

*\*No extended abstract available at press time*





**Technical Papers**



# A NEW GENERATION OF OPTICAL SYSTEMS WITH $\phi$ -POLYNOMIAL SURFACES

Kyle H. Fuerschbach<sup>1</sup>, Kevin P. Thompson<sup>2</sup>, and Jannick P. Rolland<sup>1</sup>

<sup>1</sup>Institute of Optics  
University of Rochester  
Rochester, NY, USA

<sup>2</sup>Synopsys Inc.  
Pittsford, NY, USA

## INTRODUCTION

Diamond turning technology has evolved to include the fabrication of surfaces that are not rotationally symmetric. The specific technology advance in diamond-turning is the addition and integration of servos into the axes geometry in either a fast tool servo or slow slide servo configuration [1]. This technology allows non-rotationally symmetric surfaces to be manufactured on any diamond machine-able substrate in a cost-efficient manner. With this advance, which is in-place at a few U.S. facilities, it is now possible to create compact, optical systems with large fields of view and diffraction-limited performance in the mid and long wave IR (3-5  $\mu\text{m}$  and 8-12  $\mu\text{m}$ ). In one particular case, to be presented, a diffraction limited ( $\lambda/10$ ), long wave infrared (LWIR), F/1.9, 10° full field of view sensor telescope is designed by introducing these non-symmetric surfaces into the optical surface prescription. The design is based on patent 5,309,276 from 1994 that presents a four mirror optical system having the largest planar, circular input aperture in the smallest overall spherical volume [2].

The optical design methods that are needed to leverage this new fabrication technology build on Full Field Displays (FFD) that were developed within CODE V lens design software using funding provided by the DARPA program for conformal optics [3], led by L.N. Dursvala. These optical design methods are based on a complete theory of the image quality aberrations for optical systems without rotational symmetry discovered in the 1970s [4]. Using the nodal structure of aberrations in non-symmetric optical systems and FFD as an aid, specific aberrations can be targeted and their impact reduced during optimization [5].

With the design and fabrication methods in place, it remains to develop affordable methods

to test these new surfaces. A method, to be presented here, is proposed for testing a non-rotationally symmetric surface with a conventional Fizeau type interferometer. The system uses several simple (singlet) optical elements in an Offner null configuration in addition to an active optical element (deformable mirror) to create an asymmetric reference wavefront that allows for conventional null-based interferometry.

## $\phi$ -POLYNOMIAL SURFACES

A  $\phi$ -polynomial surface takes the form:

$$z = F(r, \phi) \quad (1)$$

where the sag,  $z$ , is represented by some function that depends on the radial component,  $r$ , and the azimuthal component,  $\phi$ . With the sag of the optical surface taking this form, the surface is no longer limited to be rotationally symmetric as is the case when the sag only depends on the radial component, that is,  $z = F(r)$ . Moreover, with this additional degree of freedom the surface can correct for asymmetric aberrations (i.e. coma) within an optical design.

## Zernike Polynomial Surface

The  $\phi$ -polynomial surface type that is used for the work presented in this paper is a Zernike polynomial surface described by the following equation:

$$z = \frac{Cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} + \sum_{j=1}^{37} C_j Z_j \quad (2)$$

where  $z$  is the sag of the surface,  $c$  is the vertex curvature,  $k$  is the conic constant,  $r$  is the radial component,  $Z_j$  is the  $j^{\text{th}}$  FRINGE Zernike polynomial, and  $C_j$  is the coefficient of  $Z_j$ . Each  $Z_j$  is a polynomial in radial coordinates ( $R$  and  $\phi$ ) where  $R$  is a quantity normalized to a radius

$R_{norm}$ , that is,  $R = \left(\frac{r}{R_{norm}}\right)$ . A table summarizing the FRINGE Zernike polynomials can be found in [6].

### LONG WAVE INFRARED IMAGER EXAMPLE

The Zernike polynomial surface type described above has been applied to create a specific example, a long wave infrared (LWIR) three mirror imaging system as shown in Figure 1 below. The system operates at F/1.9 over a  $10^\circ$  full field of view and is designed to interface to a 320x240 pixel, 25  $\mu\text{m}$  pixel pitch, microbolometer camera.

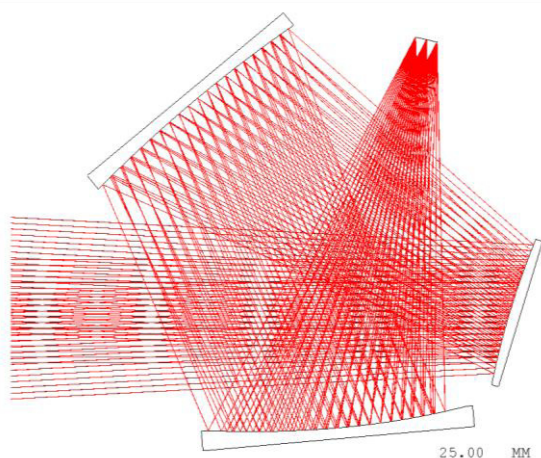


FIGURE 1. Layout of LWIR imaging system using  $\phi$ -polynomial (Zernike) surfaces.

As can be seen from Figure 1 the system provides a compact geometry and a large input port in a small spherical volume. This unique property is made possible by tilting the powered mirrors at large angles (on the order of twenty degrees). Consequently, the system is dominated by aberrations like astigmatism and coma and requires a non-rotationally symmetric surface to reduce the impact of these aberrations.

### Image Performance

The three Zernike polynomial surfaces have been optimized with nodal-based Zernike coefficient optimization using terms up to Z16 in FRINGE polynomial notation. The image performance of the final optimized system is presented in Figure 2 where the RMS wavefront error at a wavelength of 10  $\mu\text{m}$  is shown across the detector's full field of view. The system exhibits superior performance due to the fact that the surface can be made comatic (that is, the surface is a  $\phi$ -polynomial) and can correct

for aberrations that are not correctable with other non-rotationally symmetric (toroidal) surfaces.

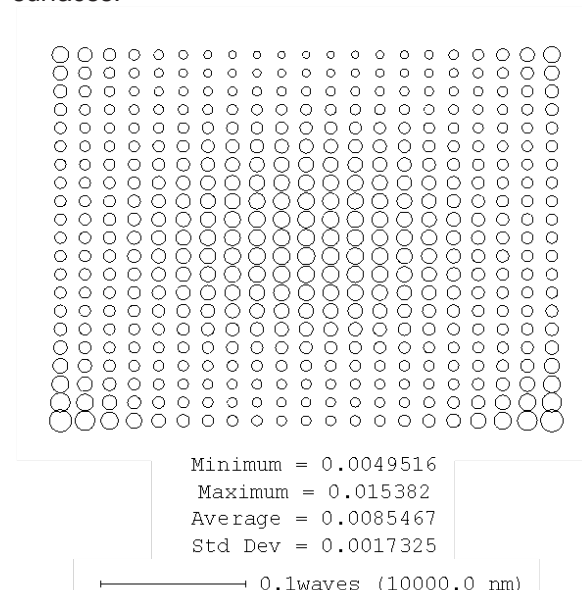


FIGURE 2. RMS wavefront error of the LWIR imaging system over a  $8^\circ \times 6^\circ$  full field of view at F/1.9.

### Surface Shapes

The sag of the primary, secondary, and tertiary mirrors is shown in Figure 3. As can be seen from Figure 3 (left), the primary and secondary mirrors deviate from the fabrication reference sphere (sphere that connects the center and edge sag values) by a hundred microns. The tertiary mirror has even larger deviation and varies from its reference sphere by as much as 635  $\mu\text{m}$ .

The Zernike composition of the mirror surfaces can be seen within Figure 3 (middle) where the sag is shown with the piston and power Zernike terms subtracted. The sag difference for the secondary and tertiary mirrors resembles a saddle shape, synonymous with astigmatism. This result is expected because astigmatism is the dominant aberration of the system and requires the most correction by the mirror surfaces. Moreover, when the astigmatism Zernike term is also subtracted, Figure 3 (right), an asymmetry can be seen along the vertical direction for all three mirror surfaces and is due to the comatic terms within the surface description which are used for coma correction in the system.

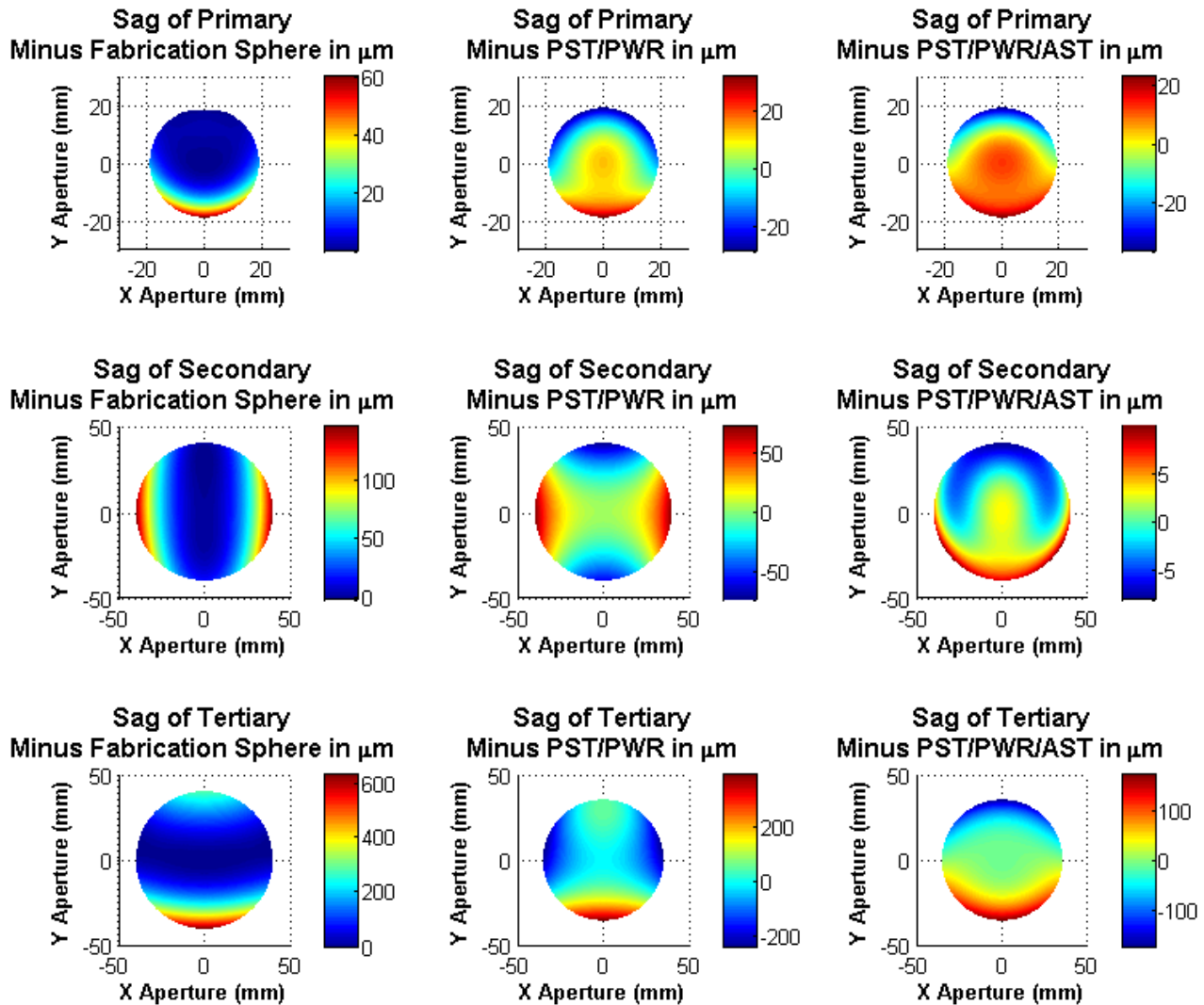


FIGURE 3. The sag with fabrication reference sphere removed (left), sag with the piston (PST) and power (PWR) Zernike terms removed (middle), and sag with the piston, power, and astigmatism (AST) Zernike terms removed (right) of the three mirror surfaces for the Zernike polynomial surface system: primary mirror (top), secondary mirror (middle), and tertiary mirror (bottom).

#### OPTICAL SURFACE METROLOGY

As shown in the section above, the three mirror surfaces of the LWIR system deviate from a sphere by a large amount. As a result, the dynamic range of a conventional interferometer is insufficient to measure the optical surface during fabrication. However, with the use of several simple null elements in a certain configuration, the deviation between the test and reference wavefronts can be lessened bringing it within the dynamic range of the interferometer.

The proposed testing configuration for the secondary mirror is shown in Figure 4. The

system consists of a conventional Offner null lens configuration [7] but with the mirror under test tilted to null the astigmatic terms present in the mirror surface. The Offner null lens consists of a focusing lens and field lens near the intermediate image. The shape (curvatures) of the front lens generates the amount of spherical aberration needed to correct for the secondary mirror. The field lens provides pupil conjugation so that higher-order aberrations are not introduced into the test wavefront.

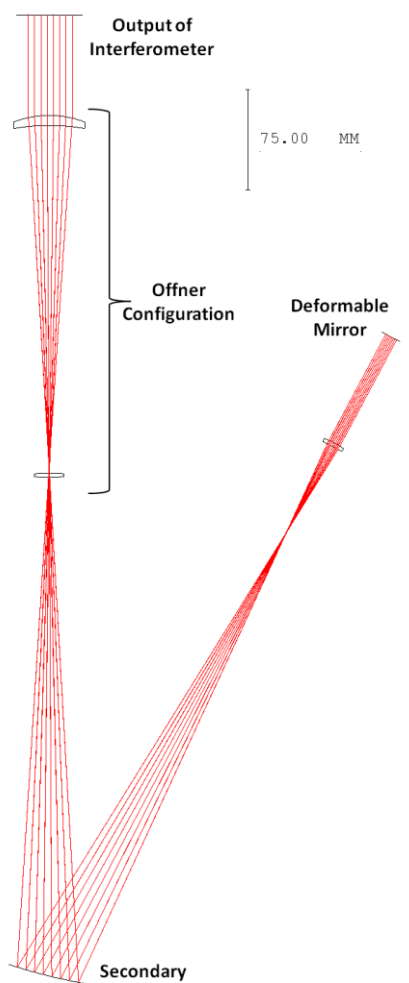


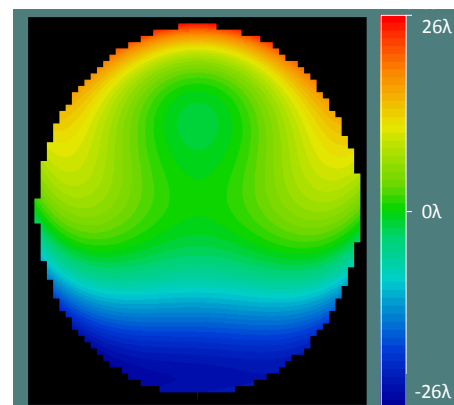
FIGURE 4. Proposed testing configuration for the secondary mirror to be coupled with a conventional Fizeau-type interferometer.

The second arm of the system provides retro-reflection so that the system can operate in a double pass configuration without inversion. However, the flat mirror that reflects the wavefront back on itself is an active element, that is, an actuated, deformable membrane mirror. With this additional degree of freedom, additional correction of the wavefront can be made to minimize the deviation between the test and reference wavefronts. As in the Offner configuration in the first arm of the system, the pupils of two mirrors must be conjugated to one another.

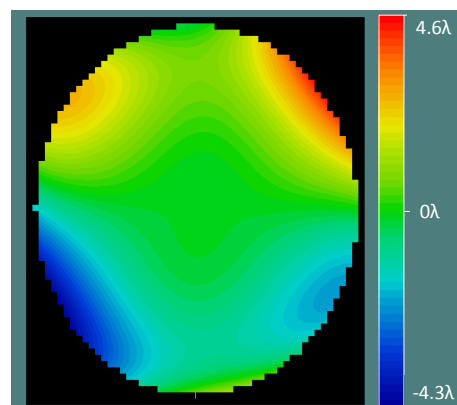
As an example, a simulation of the wavefront exiting the system before and after correction by the deformable mirror is shown in Figure 5. As can be seen from the figure, before the system has been corrected by the deformable mirror,

there is a  $50\lambda$  (at 633 nm) P-V deviation of the wavefront from a flat reference wavefront. In this configuration, the fringe density will be too great to measure the secondary mirror. However, after correction of some comatic terms with the deformable mirror, the P-V departure from flat is on the order of  $9\lambda$  and within the dynamic range of the interferometer.

The correction of comatic terms in the exiting wavefront is limited to the stroke of the deformable mirror; therefore, it may be possible that not all the comatic terms present in the Zernike surface can be removed from the exiting wavefront. Thus the residual will have to be subtracted within software during post-processing of the results. An on-going experiment within the research group is to determine the correction of comatic terms possible with the deformable mirror and assess the error induced by removing the residual comatic terms within a software environment.



(a)



(b)

FIGURE 5. Wavefront exiting the null optic configuration before (a) and after (b) correction with the deformable mirror. Values presented are given in waves at 633 nm.



## CONCLUSIONS

With the emergence of servo configured diamond-turning machines that enable the fabrication of  $\phi$ -polynomial surfaces, the utility of designing with non-rotationally symmetric surfaces is shown in this study. The design presented is a substantive leap forward in achieving large fields of view with compact solutions. Moreover, a method that utilizes a conventional interferometer with a null setup is presented for measuring a  $\phi$ -polynomial surface with at least a hundred microns deviation from a best fit sphere. Furthermore, the advance in fabrication technology allows for the immediate fabrication of the surfaces, which we expect to be underway within the next couple months.

## ACKNOWLEDGEMENTS

We thank the Frank J. Horton Research Fellowship, II-VI Foundation, and the NYSTAR Foundation for supporting this work. We thank Synopsys Inc. for the student license of CODE V.

## REFERENCES

- [1] Tohme YE, Lowe JA. Machining of freeform optical surfaces by slow slide servo method. Proceedings of the American Society for Precision Engineering Annual Meeting; 2003.
- [2] Rodgers JM; Catoptric optical system including concave and convex reflectors. US patent 5,309,276. 1994.
- [3] Thompson KP, Rodgers JM. Conformal optics: key issues in a developing technology. Optics and Photonics News. 1997;8(10):24-30.
- [4] Thompson KP. Beyond Optical Design: Interaction between the lens designer and the real world. Proceeding of the SPIE 554 (IODC); 1985.
- [5] Rodgers JM, Thompson KP. Benefits of Freeform Mirror Surfaces in Optical Design. Proceedings of the American Society for Precision Engineering Annual Meeting; 2004.
- [6] ORA. CODE V Reference Manual. 2009.
- [7] Malacara D. Optical shop testing. Hoboken, New Jersey: John Wiley & Sons, Inc.; 2007. p. 462.

# ANAMORPHIC IMAGING WITH THREE MIRRORS: SURFACE FORMS

Joseph M. Howard

Optics Branch (Code 551), NASA Goddard Space Flight Center,  
Greenbelt, MD 20771 USA

**Abstract:** Optical designs for unobstructed, plane-symmetric, anamorphic systems composed of three mirrors are discussed with examples presented from a class of systems with fixed packaging constraints. The surface forms resulting from this design survey are presented.

Recently, Howard and Stone presented methods for designing reflective anamorphic optical systems with a plane of symmetry [1]. This work was based on previous work using Hamiltonian methods [2,3], and is related to other applications applying these methods to the design of unobstructed reflective systems [4]. This paper also considers plane-symmetric systems of three mirrors, but releases the constraint that the mirrors be conic. The optical systems are allowed to be anamorphic, that is, having varying focal lengths in lateral coordinates such that a rectangular object is imaged to a square.

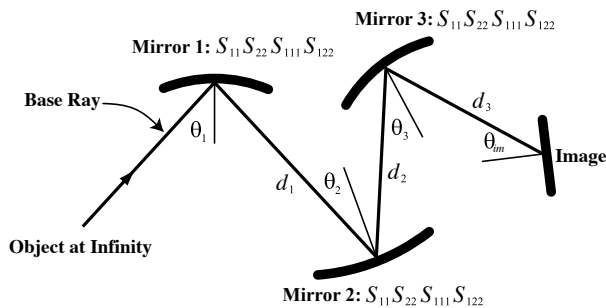
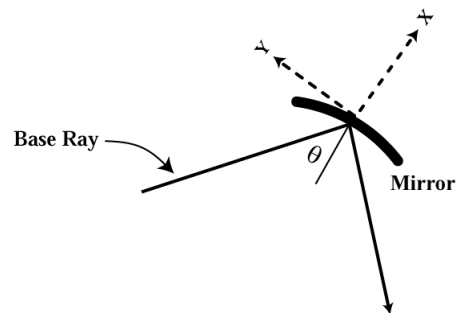


Figure 1. Nineteen construction parameters for a three-mirror system.

In Figure 1, the base ray and the 19 construction parameters associated with a plane-symmetric system of three mirrors are illustrated. The base ray is the ray that originates at the center of the field and passes through the center of the pupil. (In a centered system, for example, the base ray would travel along the axis of symmetry.) Only consider the case where the object is at infinity is considered here, but similar results can be obtained for systems at finite conjugates. The construction parameters are: the separations for

each segment along the base ray ( $d_1, d_2, d_3$ ), the tilts of the object, image, and the mirrors ( $\theta_1, \theta_2, \theta_3, \theta_{im}$ ), the surface shape parameters ( $S_{11}, S_{22}, S_{111}, S_{122}$ ) for each mirror (12 total). Each construction parameter represents one degree of freedom to the designer.

In Figure 2, the surface shape parameters are shown to be defined as the coefficients of the Taylor expansion of the mirror about the point where the base ray intersects (i.e. basal point). This notation is readily available in optical design software and is typically called "anamorphic asphere", or some variant. If desired, these four parameters can be reduced to three degrees of freedom by constraining the mirror to be a conic section (on or off-axis), but doing so results in a disconnected configuration space where no solutions exist [5]. As such, only anamorphic aspheres are considered here.



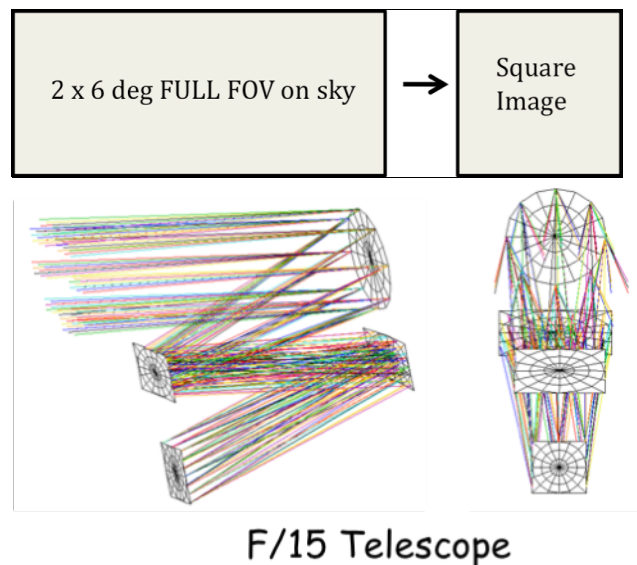
$$S(Y) = 1/2 (S_{11}Y^2 + S_{22}Z^2) + 1/6 Y(S_{111}Y^2 + 3S_{122}Z^2) + O(4)$$

Figure 2. Surface shape parameters and equation used to describe mirrors.

Anamorphic systems should be considered whenever an optical system under utilizes a given detector format, such as the case investigated here where a rectangular field is imaged to a square detector. Alternatively, anamorphic systems can also be applied to image a square field to a rectangular detector. By building in anamorphism, one could fully utilize the given detector, and post-process the images to be non-anamorphic, if desired.

Systems have been reported to improve their capability through using anamorphic systems [6-7]. Other uses include pupil slicing and grazing incidence interferometry [8]. Additional applications include earth-observing “push-broom” style imaging systems, wide-field thermal infrared sensors, as well as observational astronomy.

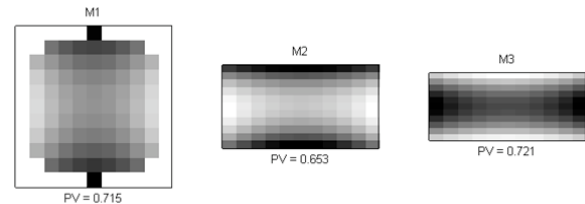
In reference [1], a design survey is performed with example systems presented. In this paper, the mirror surfaces resulting from the design survey are described, and examples presented. One example is shown below. In this figure, a telescope is shown along with a representation of how the field of view is anamorphically imaged to a square detector, where the wide horizontal angle is compressed by a factor of three.



*Figure 3. Field of View (FOV) compression for example telescope.*

Breaking symmetry on system distortion leads to broken symmetry in the figures for each of the mirrors. Figure three illustrates the departure from a best-fit sphere for each of the three mirrors. M1 refers to the primary, M2 the

secondary, and M3 the tertiary mirrors. The peak-to-valley (PV) departure is given in units of mm under each mirror. Note that plane symmetry is enforced, and can be seen in the plots in Figure 4. These and other systems will be discussed in this presentation.



*Figure 4. Surface Figure departure from a sphere (units = mm).*

## References

- [1] Joseph M. Howard and Bryan D. Stone, "Anamorphic Imaging with Three Mirrors: a survey," Proc. SPIE 7652 (2010).
- [2] Bryan D. Stone and G.W. Forbes, "Foundations of first-order layout for asymmetric systems: an applications of Hamilton's methods," J. Opt. Soc. Am. A 9, 96-110 (1992).
- [3] Bryan D. Stone and G.W. Forbes, "Foundations of second-order layout for asymmetric systems," J. Opt. Soc. Am. A 9, 2067-2082 (1992).
- [4] Joseph M. Howard and Bryan D. Stone, "Nonanmorphic imaging with three conic mirrors," Proc. SPIE 4832, 25 (2002).
- [5] A discussion of representing a conic surface as a Taylor expansion about an off-axis point can be found in Section 6 of G.W. Forbes and Bryan D. Stone, "Hamilton's angle characteristic in closed form for generally configured conic and toric interfaces," J. Opt. Soc. Am. A 10, 1270- (1993). By considering equations 2.4 of Ref [3], i.e. specifically the square root terms, one can readily see that not all realizations of the S parameters will result in real values for the conic profile.
- [6] E. Eisner, "Brighter Spectrographic Images by the Use of Anamorphic Optics," Applied Optics, Vol. 2, No. 7, 755-7 (1963).
- [7] D.E. Aspnes and S. M. Kelso, "Common-axis rotationally symmetric anamorphic mirror combinations: application to synchrotron-radiation beam lines," J. Opt. Soc. Am. Vol. 71, No. 8, 997-1001 (1981).
- [8] Paolo Spanò, "Free-forms optics into astronomical use: The case of an all-mirror anamorphic collimator," Proc. SPIE 7018, 701840, (2008).

# **STRUCTURED SURFACES FOR BIOMIMETIC MICRO-OPTICAL SYSTEMS**

**Aaron T. Cannistra, Brian S. Dutterer; Matthew A. Davies  
and Thomas J. Suleski  
University of North Carolina at Charlotte  
Charlotte, NC 28223**

It is known from nature that animals whose biological optical systems employ hierarchical features spanning many orders of magnitude tend to have exceptional survival advantages. A prime example is the compound insect eye ("fly's eye"), consisting of a curved array of microlenses enabling a wide field of view, with integrated sub-micron surface textures ("moth's eye" structures) to minimize reflected light. The eye of the mantis shrimp utilizes a conceptually similar architecture, but with microscale to nanoscale structures on and within the compound eye to enable preferential imaging of specific spectral ranges as well as specific polarization states. Engineering of such hierarchical optical systems could enable compact solutions for medical diagnostics, military surveillance, solar energy collection, and advanced imaging systems. However, conventional optical components most often have little or none of the complexity discussed due to limitations inherent in typical fabrication methods. Fabrication of secondary optical structures on curved surfaces present particular challenges.

In this paper, we explore engineering approaches to realize hierarchical optical systems inspired by nature by integrating macro-scale curved surfaces with structured optical structures on the micro and nano-scales. Examples include microlenses, anti-reflection surfaces, polarization selective surfaces, and spectral filters. Design and modeling considerations based on both geometrical and physical optics are presented. Multiple fabrication approaches are discussed, including free-form diamond machining, lithographic patterning, nanoreplication, and hybrid approaches. Advantages and disadvantages of different approaches are discussed, and initial experimental results are presented.

# A NEW WAY TO MOLD LENSES WITH FREEFORM AND STRUCTURED SURFACES

**William T. Plummer**  
**WTP Optics, Inc**  
**Concord, Massachusetts, USA**

## INTRODUCTION

The thermal infrared spectrum is attracting interest now because of new digital image-capturing devices, such as uncooled bolometer arrays. But these devices still need lenses to form their images. If we want to use an aspheric surface here and there in an optical design, conventional wisdom only offers us relatively expensive diamond-turned components or molded chalcogenide glasses.

A newly patented technology offers a way to manufacture lenses in high volume for use in the infrared, out to 20 or even 50 microns wavelength, with excellent transmission and a variety of available material properties, all for an attractively low cost [1].

We can now make spherical, aspheric, or freeform infrared lens components, diffractive infrared optical elements, and even lens and prism arrays and more general structured surfaces, with the same versatility, convenience, and precision that we enjoy when molding freeform and structured optical plastics for use at visible wavelengths [2-6].

I will discuss an example structured surface that was designed and manufactured in large quantities for visible light. The manufacturing technologies used to produce it can now also be used for making many different structured surfaces usable in the thermal infrared.

## INFRARED MOLDING TECHNOLOGY

The new molding technique uses a finely divided powder, preferably dry nanocrystals, of a material such as Potassium Bromide or Cesium Iodide, to fill a mold. These nanocrystals are preferably 10% or less of the wavelength in diameter. They are firmly compressed at room temperature to produce a solid optical part. A conventional hydraulic press can be used.

The mold is constructed much like the molds used for making plastic lenses, but can be simpler because heating and cooling passages are not needed, and the lens material is loaded

in directly by weight, not injected through a sprue and runners. The optical mold surfaces can be made of ground and polished stainless steel, or diamond turned or electroformed nickel, just as for plastic molding.

The resulting molded polycrystalline optical part does not require secondary polishing. If desired, the optical part can be molded directly into position in its final mounting cell, made of plastic or metal, to avoid all edging or trimming, or even an assembly step.

The most effective lens materials for this new application are hygroscopic to some degree, but the manufactured part can be protected from moisture in a variety of ways. These include an evaporated thin conformal polymer coating, a polymer film sleeve, a polymer spin coating, or merely sealing the part in a mounting cell between non-hygroscopic optical components.

This new capability for manufacturing infrared lenses and other optical components is directly based on a very old and established chemical laboratory art called "solid matrix sampling", in which a small amount of a powdered sample is mixed uniformly with a powdered transparent base material and compressed into a flat solid block for spectrometric analysis. More information about this new manufacturing technology can be found in [1].

I will present sample infrared lens designs that make use of molded aspheric surfaces on Potassium Bromide. I will show photographs of other inorganic polycrystalline transparent parts formed by this cold powder molding, to demonstrate the new capability to produce both freeform and structured surfaces for use in the infrared.

## STRUCTURED SURFACE EXAMPLE

Structured surfaces on plastic optical parts have usually been manufactured with a nickel electroformed molding tool, and the same method can now be used for making structured surfaces for these much longer wavelengths.

One example of an early manufactured plastic structured surface for visible wavelengths is the reflective Fresnel focus screen used in the Polaroid SX-70 camera [3], a commercial product that also incorporated two freeform plastic optical lenses [2,3]. That focus screen combines a diamond-ruled Fresnel mirror surface, itself designed with rotational asymmetry, but also made with a controlled diffuse surface granularity appropriate for the f/number of the camera. That one reflective surface functions as both field lens and focus screen. Several million of these cameras were made, and they are readily available on eBay.com.

For optimum performance at f/8, the desired micro slopes imposed randomly on all the Fresnel surface facets have to reach about  $2^\circ$  as the best compromise between image brightness and focus screen effectiveness. With a lateral size averaging about 25 microns, on Fresnel facets 125 microns wide, the random structure needed is only about 1/2 wavelength deep, just barely enough so that the reflected diffusion can be described by geometric optics. The slopes and depth are both critical, but after a metal tool was made it was easy to control both properties by either compression molding (from 1972 to 1986) or later by injection molding.

The required depth, size, and angular granularity of the structured surface was first achieved by airbrushing a compression-molded plastic master part with a special solvent. Each individual tiny drop of solvent hit and wet the surface, dissolved some of the substrate material, then evaporated and left the surface just slightly disturbed. The angular changes produced in this way were controlled by doping (about one part per thousand) of a different plastic, chosen empirically, in the solvent. Different plastic dopants gave different distributions of the granular surface slope, perhaps by functioning as a wetting agent when each droplet struck the substrate.

After the plastic master was made it was aired to evaporate all solvent, then electroformed with plated nickel to make the production metal molding tools [7,8]. The molded plastic focus screens were made reflective with evaporated aluminum and a dielectric overcoat.

Diffraction surfaces, including holographic surfaces, have often been molded on plastic, and now can be manufactured for the infrared

on these inorganic solids by using the same kind of electroformed nickel molding tool [1].

Structured surfaces with diffractive optical power can be used for splitting energy between different image distances or directions, for achromatizing, for athermalizing [9,10], for achieving different design results for separate wavelength bands, and for visual display.

## REFERENCES

- [1] Plummer, W. Solid State Method and Apparatus for Making Lenses and Lens Components. U.S. Patent #7,591,557 B2. 2009. Others pending.
- [2] Plummer, W. Free-Form Optical Components in Some Early Commercial Products, Extended Abstract, *Proceedings ASPE Winter Topical Meeting on Free-Form Optics: Design, Fabrication, Metrology, Assembly*. 2004; 68-71.
- [3] Plummer, W. Unusual Optics of the Polaroid SX-70 Land Camera. *Applied Optics*. 1982; 21: 196-202.
- [4] Baker, J and Plummer, W. Analytic Function Optical Component. U.S. Patent #4,650,292. 1987.
- [5] Plummer, W, Mader, J, Roblee, J, and Van Tassell, J. Precision Engineering at Polaroid. *Proc. of the Pre-Conf. Day*, pp. 24-29, Precision Engineering in Industry International State of the Art, Eighth Int. Precision Eng. Seminar, Université de Technologie de Compiègne, France; M. Bonis, et al., Ed. <http://wtptoptics.com/PEdoc.html> 1995.
- [6] Plummer, W, Baker, J, and Van Tassell, J. Photographic Optical Systems Using Nonrotational Aspheric Surfaces. *Applied Optics*. 1999; 38: 3572-3592.
- [7] Plummer, W. Focus Screen Optimization. *Applied Optics*. 1975; 14: 2762-2765.
- [8] Plummer, W. Smoothly Granulated Optical Surface and Method for Making Same. U.S. Patent #3,718,078. 1973.
- [9] Londoño, C, Plummer, W, and Clark, P. Athermalization of a Single-Component Lens with Diffractive Optics. *Applied Optics*. 1992; 32: 2295-2302.
- [10] Plummer, W and Londoño, C. Methods and Means for Reducing Temperature-Induced Variations in Lenses and Lens Devices. U.S. Patent #5,260,828. 1993.



# FREEFORM SURFACE FABRICATION IN CYLINDRICAL COORDINATES

**Kenneth P. Garrard, Alexander Sohn, and Thomas A. Dow**  
**Precision Engineering Center**  
**North Carolina State University**  
**Raleigh, North Carolina, USA**

## ABSTRACT

Diamond turning lathes augmented with fast tool servo technology are an efficient and accurate means of producing precision optical and mechanical surfaces. In this paper, a comprehensive approach to the fabrication of freeform surfaces with diamond tools is presented. A variety of fast tool servos have been developed at the Precision Engineering Center (PEC) over the past 25 years. The latest system, FLORA II [1], has a 6 mm range and has demonstrated 2 nm RMS surface finish and 31 nm RMS figure error machining a 50 mm diameter tilted flat with 1 mm peak-to-valley excursion at 600 rpm. This is comparable to the best results obtained from the base diamond turning machine, an ASG2500. FLORA has its own DSP based controller and is fully integrated into the machine. Matlab™ software has been developed to generate tool path data for machining complex surfaces with the FLORA system. This software can also create design data for the spherical coordinate measuring machine, *Polaris3D* [2], “closing the loop” from design to fabrication to metrology. Finally two examples are discussed. One is a 100 mm aperture far off-axis segment of a biconic mirror for an infrared spectrometer and the other is a small, multi-element collimating optic for a diode laser.

## INTRODUCTION

To machine a freeform surface, a non-rotationally symmetric (NRS) tool path must be developed. This involves translating the native surface description into machine coordinates, correcting for the shape of the tool, decomposing the result into a rotationally-symmetric (RS) component and an NRS component and compensating for the dynamic limitations of the fabrication hardware. A closed form solution for decomposition of any segment of a conic surface has been derived and for any surface with continuous first order cross derivatives a tool shape compensation algorithm has been developed. However, a purely

numeric approach is used here to formulate a comprehensive solution to the tool path generation problem. Details of the steps involved are presented below after a brief description of the FLORA II fast tool servo.

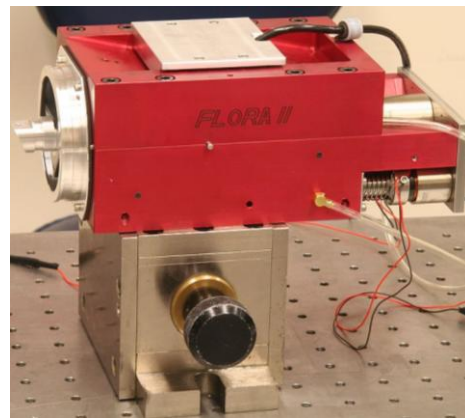


FIGURE 1. FLORA II fast tool servo.

## The FLORA II Fast Tool Servo

The FLORA II (Fast LOnge Range Actuator) shown in Figure 1 has been developed over the past several years at the PEC. It is integrated into an ASG2500 diamond turning machine and is operated by a PMDi DMC-100 controller. The actuator is a triangular cross-section silicon carbide piston supported by New Way air bearings. The 0.36 kg moving mass is driven by a voice coil motor. It is actively counter-balanced with two identical voice coil motors moving the same total mass. A Sony BH25 laserscale with 244 pm resolution provides position feedback over the full 6 mm stroke. The servo control is proportional-integral-derivative with velocity and acceleration feed-forward at 20 kHz.

The graphical user interface for the FLORA II control system is shown in Figure 2. This software provides user controls to start and stop the actuator, manually position the tool for machine setup and to download interpolator data files for freeform surface fabrication. The

tool position, calculated command set point and axes and spindle positions can be acquired and streamed to the host PC hard drive indefinitely at up to the full servo update rate.



FIGURE 2. FLORA II user interface.

### Command Generation

The controller generates position, velocity and acceleration command signals for the servo loop as a function of the spindle and axes positions of the DTM. A bilinear interpolation function is implemented to represent any surface as a plaid, but not necessarily uniformly spaced, 2D grid of set points. Velocity and acceleration are calculated with balanced finite differencing. Interpolation of tool position at an arbitrary point,  $P_k$ , inside the data grid is illustrated in Figure 3.

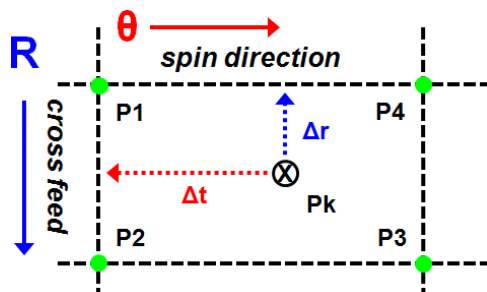


FIGURE 3. Bilinear interpolation of position.

The position set point is calculated from  $P_1$  to  $P_4$  as,

$$P_k = P_1 \times (1 - \Delta r) \times (1 - \Delta t) + P_2 \times \Delta r \times (1 - \Delta t) + P_3 \times \Delta r \times \Delta t + P_4 \times (1 - \Delta r) \times \Delta t$$

This formula can be used to interpolate velocity and acceleration as well if grids containing those quantities were available. However to minimize the RAM required, a balanced finite difference is used to estimate  $V_1$  to  $V_4$  and  $A_1$  to  $A_4$ . Note that  $V_1$  and  $V_2$  require position points earlier (to the left) from the grid and  $V_3$  and  $V_4$  require

points from the right in the grid. Similarly estimating accelerations  $A_1$  to  $A_4$  are made by expanding the region of the grid to 12 points. The final values for velocity and acceleration must be scaled according to the spindle speed and cross feed velocity, which are continuously updated by the controller. Note that at each servo update cycle the next point ( $P_{k+1}$ ) is at most one grid position away from current location and the intermediate results from the previous cycle can be used to reduce the computational load.

### SURFACE REPRESENTATION

Freeform surfaces are naturally described in a variety of forms. For example, radial basis functions, NURBS, Zernike polynomials, explicit functions of the form  $z = F(x, y)$ , implicit functions of the form  $F(x, y, z) = 0$  and 3D point clouds (arbitrary or regularly spaced on a grid) are all commonly used representations for opto-mechanical surfaces. The shape of a single optical surface can usually be represented as a sagittal function in cylindrical coordinates as  $z = F(\theta, R)$ . This is convenient for a turning operation; however it may not be feasible for a multiple element optical system or a system with fiducial or locating surfaces. Each optical element is also likely to be defined in its own local coordinate system and those coordinate systems need not be Cartesian.

Fabrication of a multi-element optical system with one machining setup requires all of the elements to be transformed to the coordinate system of the machine tool. The resulting cylindrical coordinate representation is then compensated for the cutter shape and reduced to a grid sag table of sufficient density to accurately reproduce the surfaces with a bilinear interpolation algorithm during machining. The grid spacing need not be uniform and should be inversely proportional to local surface curvature; that is, as the curvature increases the point spacing must decrease to keep the interpolation error with acceptable limits. The strategy is to start with over-sampled surface data and then reduce the point spacing after tool compensation, decomposition and dynamics compensation.

### TOOL SHAPE COMPENSATION

Tool shape compensation of the cutting path is best performed offline. While cutter compensation can be performed analytically for any differentiable surface, a simple, numeric



solution that does not sacrifice accuracy is preferred. The positions of the center of curvature of the tool such that the cutting edge is tangent to the desired surface can be found by projecting normal vectors into the plane of the tool. This is illustrated in Figure 4 for a circular tool that moves in the sagittal direction. If the surface data grid is in cylindrical coordinates, then the tool center positions can be easily calculated for each meridian of data after finding the radial direction slope at each point on the meridian. The curvature (change in slope divided by arc length) is evaluated to ensure that the tool radius is not too large to cut the surface. Clearance angle requirements are found by considering the spatial slope in the circumferential direction at each grid point (i.e., out of the plane of page in Figure 4).

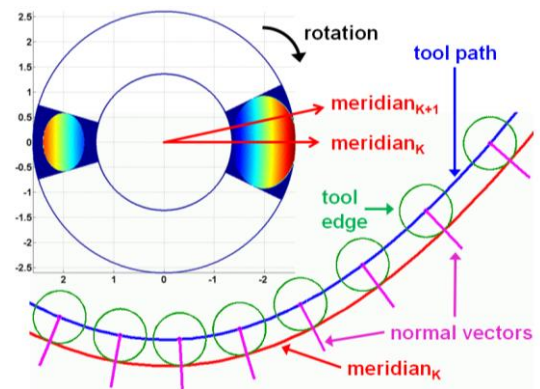


FIGURE 4. Tool radius compensation.

### SURFACE DECOMPOSITION

Even with a long-range actuator such as the voice coil driven air bearing of the FLORA II, both a high quality surface finish and rapid machining are best realized by reducing the required excursion of the servo [3]. This means decomposing the desired surface shape into an RS path to be followed by the machine axes and an NRS component for the fast tool servo.

First the data grid corrected for tool shape is fit with a sphere. If the residuals are sufficiently small then this sphere is the RS surface and the residuals are the NRS surface. Alternatively a low order radial polynomial is fit (order = 1 is a cone, 2 a parabola, >2 an asphere). Using a sphere for the underlying RS surface may be advantageous since it is easily produced and evaluated during rough machining, before the final cutting of the NRS component. From the standpoint of minimizing dynamic FTS excursion, the optimal solution is very simple to

calculate. It is the point-to-point asphere formed by taking the sagittal midpoint at each radial distance.

### DYNAMICS COMPENSATION

Before cutting the part, the dynamic response of the FTS should be considered. First the temporal slope of the motion path in the circumferential direction can be used to find the required acceleration and velocity of the FTS for each Hertz (60 rpms) of spindle speed.

The motion path for a multi-element system may include discontinuities or abrupt direction changes that are outside the clear apertures of the optical elements. In this case the motion path can be modified by smoothing the transition region and extending the aperture so that the servo response has dampened before the edge of the aperture is reached.

### Deconvolution

Slopes within apertures may be such that an unreasonably low spindle speed is required to stay within the bandwidth of the actuator. In this case a deconvolution of the time-based servo motion profile with the measured actuator dynamics can be performed to dramatically improve both form fidelity and throughput [4]. This deconvolution technique depends upon an accurate representation of the closed-loop FTS dynamics and reshapes the tool path to cancel attenuation and phase errors in the actuator motion.

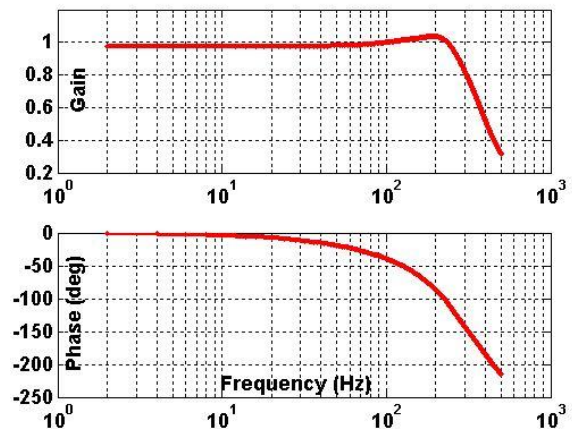


FIGURE 5. Dynamic response of long-range piezoelectric actuator.

The closed loop dynamic response of a long-range piezoelectric actuator is shown in Figure 5. As the frequency increases, the gain grows to a peak at 200 Hz and then drops rapidly at

higher frequencies. The phase angle, on the other hand, monotonically drops as shown in the lower graph. At low frequencies, the tool motion is slightly out of phase but lags  $45^\circ$  behind the input at 100 Hz. If the desired motion is input to this particular actuator, each frequency in the command stream will be modified by the dynamics of the actuator to produce a path that is much different than desired.

However, if the command stream is modified to account for the dynamics of the actuator, high fidelity in the part shape can be reached at a high operating frequency (250 Hz in Figure 5). Figure 6 shows the result of command shaping to create an off-axis sphere. The command trajectory (solid line in the center) was modified by deconvolution. The desired time-based signal was segmented into short pieces, deconvolved individually in the frequency domain, and re-transformed back to the time domain. The resulting motion command begins with a steep slope well before the actuator responds, makes a small dip to change the axis velocity prior to the peak of the sphere, descends continuously and finally adds a small wave to decelerate the tool and stop it at the DC level. This modified shape of the input command yielded a servo motion (a dashed line) close to the desired excursion. This motion command produces a shape equivalent to 250 Hz which from Figure 5 would be severely attenuated in amplitude and delayed in phase by more than  $100^\circ$ .

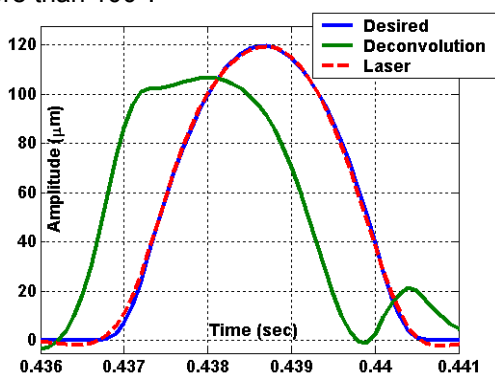


FIGURE 6. Modified command and tool motion for machining an off-axis sphere.

#### OFF-AXIS BICONIC REFLECTOR

The final optical surface in NASA's Infrared Multi-Object Spectrometer [5] is a 96x96x25 mm aluminum reflector which has a biconic shape. The aperture is decentered by  $(x_0, y_0) = (-2.01, 227)$  mm. The flat back surface is defined to be parallel to the mean normal vector from the

front surface, resulting in a tilt of  $35.3^\circ$  about the x axis. The aperture and optical axis are shown in Figure 7.

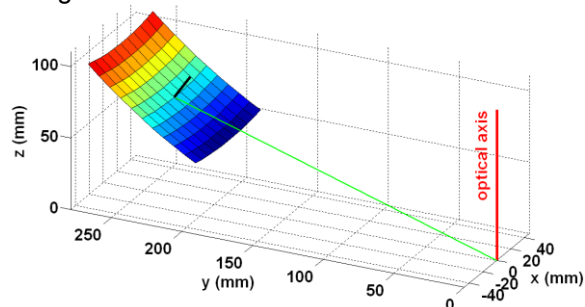


FIGURE 7. Biconic reflector surface.

A tool path for the biconic mirror was created by first removing the  $35.3^\circ$  tilt, translating the lowest point (i.e., smallest z value) to the origin. Next the surface data points were interpolated to a cylindrical mesh and tool radius compensation was performed. Finally, a least squares sphere was fit to the resulting surface to reveal the NRS component as shown in Figure 8. The range of FTS motion required is  $288 \mu\text{m}$ . Within the defined clear aperture (shown as the mesh patch) the FTS range is  $128 \mu\text{m}$ .

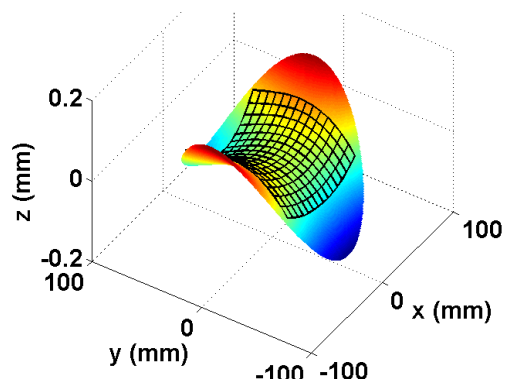


FIGURE 8. NRS component of biconic after removing the best fit sphere with radius 373 mm.

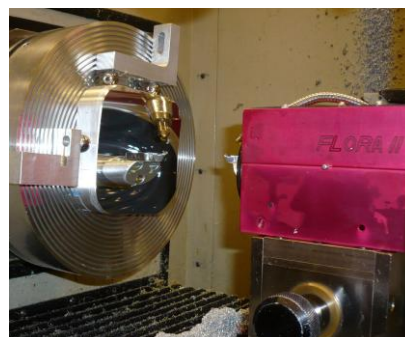
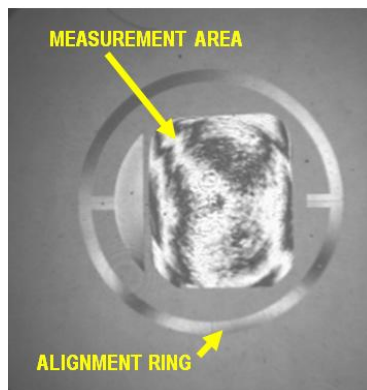


FIGURE 9. The Biconic Reflector M4 mounted on the ASG 2500 DTM. FLORA II is shown on right with the tool reflected in the mirror surface.

To test machining conditions, confirm tool centering and eliminate all systematic errors other than the fast tool servo, the best fit sphere was first machined into the substrate. The figure error of this sphere was measured at 44 nm RMS and was considered satisfactory for proceeding with the biconic surface. The biconic mirror is shown in Figure 9 immediately after final machining with the FLORA II FTS.

### **CGH Figure Measurement**

Figure measurement of free-form surfaces can be performed in a number of ways (e.g., Polaris 3D [2]), but for this application a Computer Generated Hologram (CGH) was used. The CGH includes alignment fiducials to assure correct placement of the hologram in the interferometer. Initial alignment for tip and tilt of the part substrate and the CGH plane is performed with a planar reference. Then a spherical CGH is placed in the converging beam of an F1.2 spherical reference. Lateral alignment and focus of the CGH mount is performed with this specially made holographic optic. The CGH alignment to the interferometer is fine-tuned using the spherical reference ring around the part measurement area as shown in Figure 10.



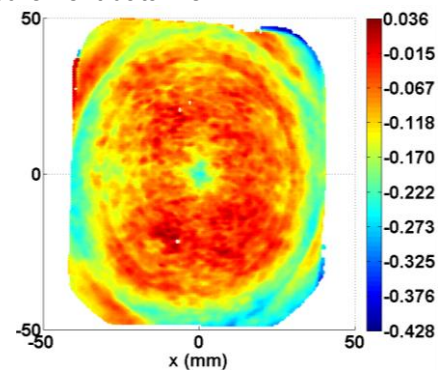
**FIGURE 10.** CGH fringe map showing the measurement area and the alignment ring.

Since the CGH is actually a diffraction grating, a 2 mm pupil is then placed at the focus and used to mask all but the first diffraction order. Finally, the part is aligned to the CGH in six degrees of freedom. This is an iterative process until a minimum error is found.

### **Results**

The surface finish measured with a Zygo NewView 5000 SWLI was 3 nm RMS. RMS figure error was 127 nm and is dominated by

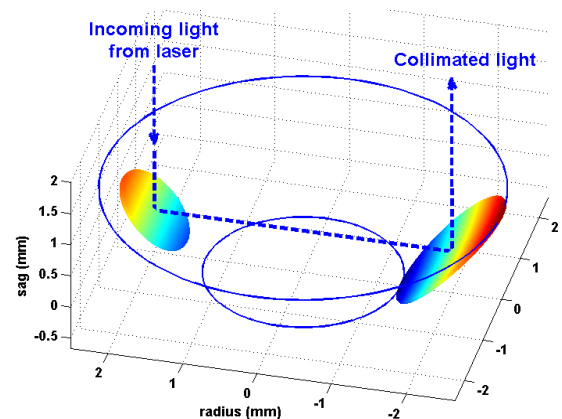
astigmatism. The shape of the astigmatism is very similar to that of the FTS excursion shown in Figure 8. Applying a gain to the FTS motion of 1.005 removes the astigmatism and reduces the RMS figure error to 43 nm as shown in Figure 11. The gain change was performed in Matlab after importing the MetroPro measurement data file.



**FIGURE 11.** CGH measurement with astigmatism removed by increasing the FTS gain. The residual error is now 43 nm RMS.

### **DIODE LASER COLLIMATOR**

A two element reflective optical system for collimating a diode laser is shown in Figure 12. Machining both optical surfaces from a single substrate guarantees alignment, however developing the tool path for the multi-element system presented several challenges. The system consists of two biconic surfaces with nominal curvatures 1/30 mm separated by 4 mm and is shown in Figure 12.



**FIGURE 12.** Laser prescan optical system.

Each surface is much “flatter” than the turning radius and thus an abrupt tool direction change is required 4 times per revolution. This is seen in Figure 13 after removing a cone from the tool path.

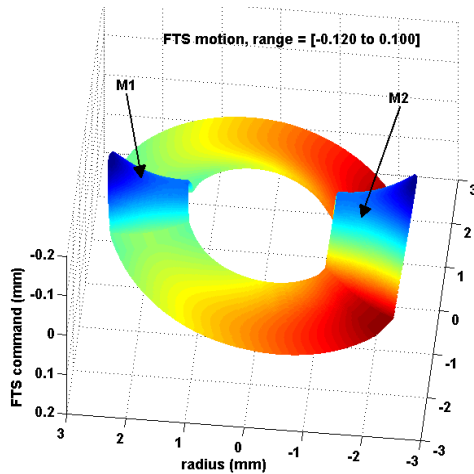


FIGURE 13. FTS component of tool path.

Since the out of aperture regions can be any shape that does not block the optical path, the apertures were extended and a small “flat” region was added to the tool path just before the transition zones. Figure 14 shows in 2D the motion path (dotted line) for one revolution of the part at a radius of 1.34 mm. Also shown (solid line) is the slope along this path, indicating that a tool with a 23° clearance angle is needed to machine this surface.

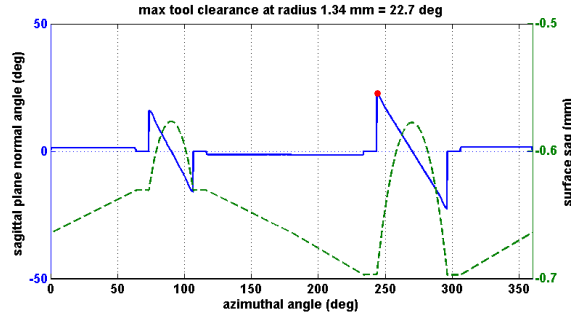


FIGURE 14. FTS tool path for one revolution.

Figure 15 shows the response of the FLORA II actuator to this commanded tool path for one revolution of the part. The following error at the edge of the aperture of M2 is about 100 nm.

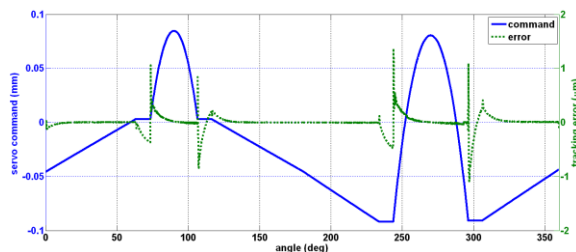


FIGURE 15. FLORA II response.

## Results

The collimator optical system was machined with the FLORA II actuator and measured with the Polaris 3D spherical profilometer [2]. The RMS error is 730 nm and is shown in Figure 16. It is apparent from Figure 15 that the aperture extension should be increased at the leading edge of each aperture and Figure 16 shows that the dominate remaining error is conical.

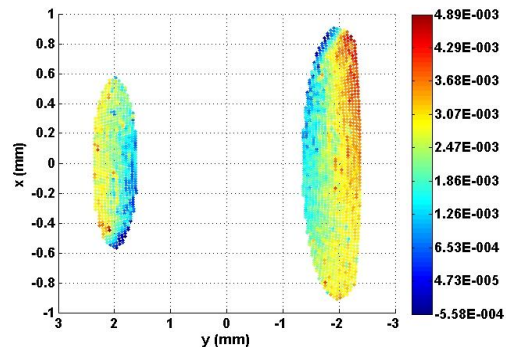


FIGURE 16. Laser prescan optic surface error.

## CONCLUSIONS

A comprehensive approach to the fabrication of freeform surfaces using the native cylindrical coordinates of a diamond turning machine augmented with a fast tool servo has been demonstrated. Matlab software has been developed for all aspects of the tool path generation problem, including decomposition, cutter shape compensation and actuator dynamics compensation.

## REFERENCES

- [1] Zdanowicz E. Design of a Fast Long Range Actuator. MS Thesis, MAE Dept. N.C. State Univ., Raleigh, NC: 2009.
- [2] Sohn A, Garrard K, Dow T. The Spherical Profilometer *Polaris3D*. Proc. of the 24th Meeting of the ASPE. 2009; 47, 43-46.
- [3] Garrard K, Bruegge T, Hoffman J, Dow T, Sohn A. Design Tools for Freeform Optics. SPIE. 2005; 5874: 95-105.
- [4] Panusittikorn W. Error Compensation using Inverse Actuator Dynamics. PhD Thesis, MAE Dept. N.C. State Univ., Raleigh, NC: 2004.
- [5] Garrard K, Sohn A, Ohl R, Mink R, Chambers V. Off-Axis Biconic Mirror Fabrication. Proc. of the 3<sup>rd</sup> International Meeting of EUSPEN. 2002; 277-280.



# FREE-FORM MANUFACTURING OF A MICROOPTICAL LENS ARRAY ON A CURVED SUBSTRATE

Sebastian Scheiding<sup>1,3</sup>, Allen Y. Yi<sup>2</sup>, Andreas Gebhardt<sup>1</sup>, Lei Li<sup>2</sup>, Stefan Risse<sup>1</sup>,  
Ramona Eberhardt<sup>1</sup> and Andreas Tünnermann<sup>1,3</sup>

<sup>1</sup>Department Precision Engineering  
Fraunhofer Institute for Applied Optics and Precision Engineering (IOF)  
Jena, Germany

<sup>2</sup>Industrial and Systems Engineering  
The Ohio State University  
Columbus, Ohio, USA

<sup>3</sup>Institute of Applied Physics  
Friedrich Schiller University Jena  
Jena, Germany

## INTRODUCTION

Accurate optical components for beam shaping, imaging and diffraction of light are manufactured by established processes such as ultra-precision machining. In addition to fabrication of metal mirrors, lenses or two-dimensional (2D) - gratings, diamond tools can also be engaged to create three-dimensional (3D) microoptical structures. As a result, geometries that are difficult or impossible to manufacture using 2  $\frac{1}{2}$ -D lithographic techniques such as photo-, gray tone or laser lithography might be fabricated using ultra-precision machining using small diamond tools with well defined cutting edges.

## FREE-FORM TURNING TECHNOLOGY

Ultra-precision turning machines are used to fabricate optics with a center of symmetry. Since 3D structures show no rotational symmetry, but rather high frequency asymmetric features, they are treated as be free-form geometries. The deviations from the rotationally symmetric reference features such as a sphere range from a few  $\mu\text{m}$  to  $\text{mm}$  or higher are manufactured on an ultra-precision lathe with additional strokes of the machining tool. The stroke of the diamond tool is synchronized to the angular position of the free-form surface in the machine's workpiece spindle. The forward and reverse motion is achieved either by the mechanical feed axis itself (Slow Tool Servo - STS), or an additional kinematic tool holder of low inertia (Fast Tool Servo - FTS). [1] For high-frequency free-form geometries the FTS technology is generally preferred.

For the conducted studies of MLA manufacturing a Nanotech 450 UPL machine with an additional NFTS-6000, from Moore Nanotechnology

Systems, LLC was used. The stroke of the FTS is  $\pm 3 \text{ mm}$ . The integrated linear scale encoder with sub-  $\text{nm}$  resolution is in a closed control loop with a voice coil actuator, that positions the air bearing slide. With a maximum acceleration of  $49.1 \text{ m/s}^2$ , the NFTS is able to precisely follow an amplitude of  $100 \mu\text{m}$  at  $160 \text{ Hz}$ . [2]

## Sample Geometry

To show the potential of micro-optics manufacturing with the free-form manufacturing technique, we have chosen a micro-lens array design with a high frequency asymmetric portion. The lens array design shown in Figure 1 is a mold insert for an injection molding tool. The molded plastic lens array is used later as a 3D microoptical imaging element to transfer features from a 3D mask onto a curved substrate using lithographic process[3]. The mold insert contains 1,219 single spherical lenslets whose vertices are arranged on a spherical surface. The outer diameter of the array is  $9.5 \text{ mm}$ .

## PROGRAMMING THE FREE-FORMS TOOL-PATH

The programming of the FTS can either be accomplished using commercial CAM-Tools such as NanoCAM 3D or proprietary software solutions. Although commercial software solutions are well developed for a wide variety of standard free-form machining applications, major drawbacks are the limited number of data points and possible approximation errors coming from the spline interpolation of high frequency free-form surfaces. The limitations of data points leads to an increased distance between the control points for the tool motion and consequently to a high

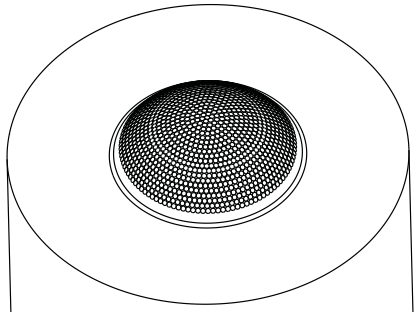


FIGURE 1. Geometry of the machined free form array containing 1,219 spherical lenslets on a sphere

shape deviation of high frequency free-forms. Typical spline interpolation errors are transitions between piecewise differentiable surfaces where spline-ringing may occur.

The representation of free-form data in the control of the FTS-System is a look up table of tool center points of the diamond tool in a polar coordinates. The streaming of data into this look up table allows the computing of large point cloud files containing some millions tool center nodes.

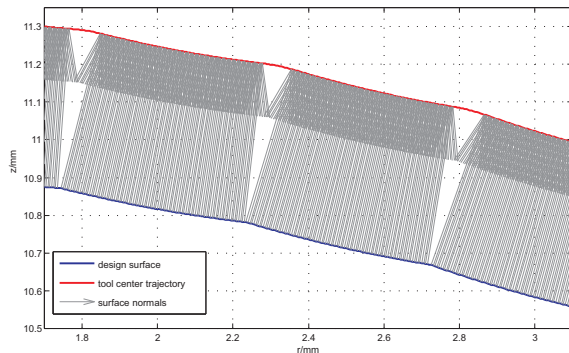


FIGURE 2. Tool radius compensation of the diamond tool tip in the radial direction

To transfer the 3D surface data with the high-frequency free-form features into a numerical code for machining, the piecewise differentiable surface is calculated in  $25.2 \cdot 10^6$  supporting points in a polar mesh. Based on this point cloud, the tool radius correction is made to account for the cutting-edge geometry. Characteristic for any turning applications is the tool radius correction only in the radial direction. The cutting edge radius of the diamond tool tip in the angular direction is in the range of  $10 \text{ \AA} - 20 \text{ \AA}$  can be neglected.

Figure 2 shows the tool radius correction for one of the 12,600 lines. Due to the discontinuities in the slope of the profile, the radius compensation is not defined in the transition area between the spheres. The missing points have to be calculated using an interpolation. Either a linear or a spline based interpolation can be applied to fill the missing data.

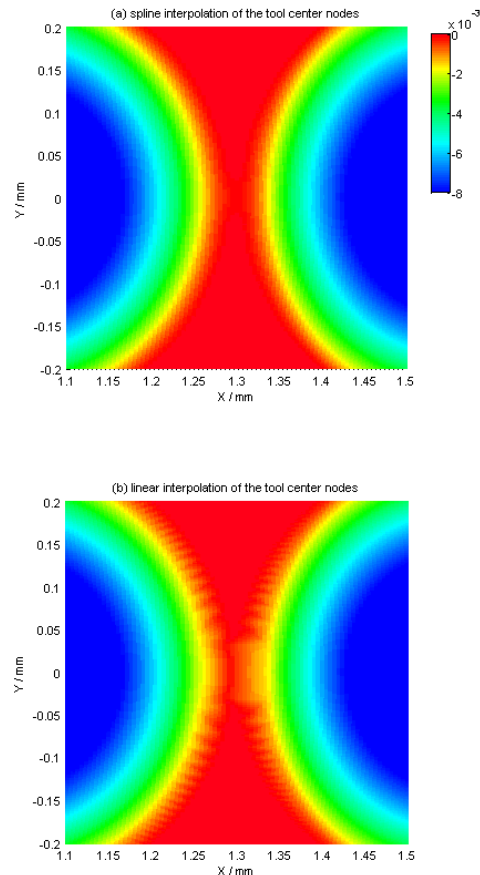


FIGURE 3. Different interpolation methods to calculate the tool center points from the surface nodes: (a) spline interpolation, (b) linear interpolation.

The difference between a spline based approach and a linear interpolation can be seen in figure 3. The linear interpolation leads to discontinuities in the radius corrected surface as a result of the discontinuous slope of the design surface. The spline based interpolation closes these gaps according to the surface slopes of the neighboring nodes. Hence a continuous and smooth edge of the lenslets can be expected.

The complete free-form portion of the tool center points are shown in figure 4. Superimposed with

the curved trajectory of the rotationally symmetric portion the geometric information for the production of this microoptical component is established.

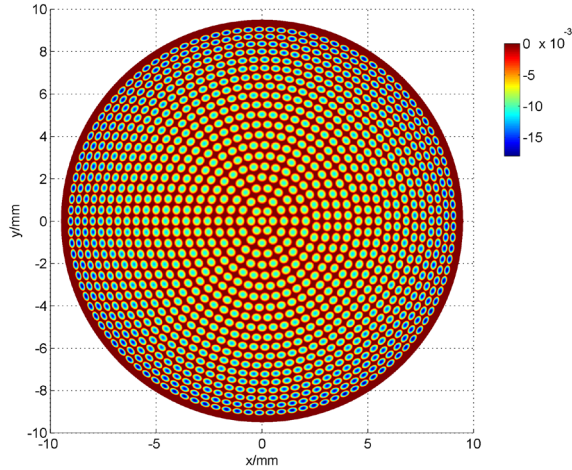


FIGURE 4. Tool path generation for the fabrication of the micro lens array on a curved surface.

#### CUTTING PARAMETERS FOR FREE-FORM MACHINING

The total FTS-stroke needed to fabricate the lens array is  $18\text{ }\mu\text{m}$ . According to the frequency response specification of the manufacturer, the FTS is able to operate at more than 200 Hz at this amplitude. Assuming a constant spindle speed, the highest necessary frequency of the FTS is expected on the outer diameter. Here 109 lenslets are machined on a common reference circle. The possible speed of 110 rpm is reduced to 25 rpm, because the excitation of  $18\text{ }\mu\text{m}$  does not follow a sinusoidal motion. To achieve a reasonable smooth surface, the feed per revolution is adjusted to be in the micron range. The cutting data are summarized in table 1. The machining time for the whole array is 80 min. The material used is a high strength aluminum alloy as mold inserts for injection molding.

The free-form micro lens array is machined in a two-tool process. The first diamond tool is used for rough cutting of the sphere and the reference surfaces, the second tool is mounted on the FTS and is used for the cutting of the hemisphere with the spherical lenslets.

#### RESULTS OF THE FREE-FORM MACHINING

After diamond servo turning, the micro lens array is cleaned and inspected to forecast the optical performance regarding scattering losses at certain wavelengths and optical performance as result of the form deviation.

TABLE 1. Cutting parameter for the free-form machining of the lens array

| Cutting Data                     |                           |
|----------------------------------|---------------------------|
| Diamond tool radius $r_\epsilon$ | 0.470 mm                  |
| Depth of rough-cut $a_{p,rough}$ | $< 18\text{ }\mu\text{m}$ |
| Spindle speed                    | 25 rpm                    |
| Feed rate                        | 0.125 mm/min              |
| Feed per rev.                    | 5 $\mu\text{m}$           |

#### Surface Roughness

For characterizing the micro roughness, a Zygo White Light Interferometer NewView 600 with a 50x objective lens is used. To distinguish between form error and roughness profile a spherical surface with a radius of 3.8082 mm is subtracted from the measured data. The surface texture is shown in figure 5. The finish of 4 nm (rms) is similar to ultra-precision diamond turning of aluminum alloys. The influence of the redundant kinematics of the FTS system is visible in the high frequent residuals in two direction.

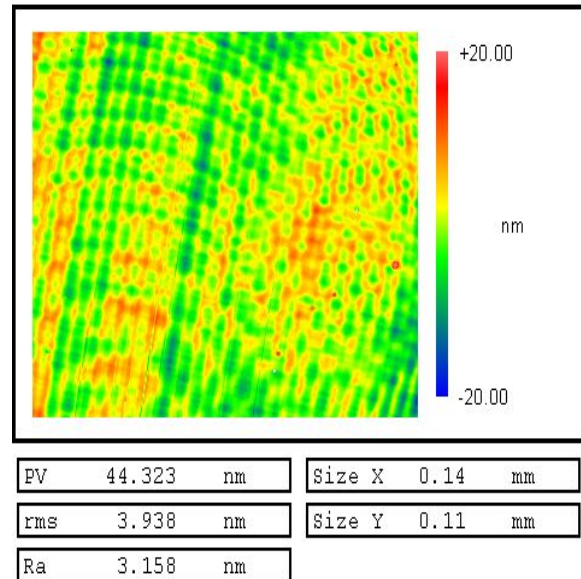


FIGURE 5. Micro roughness of the aluminum surface inside a lenslet is 4 nm (rms) measured with white light interferometry.

### Form Error

The shape deviation of the complete free-form surface is measured with a tactile 3D-profilometer UA3P-5 from Panasonic. This tactile measurement device, with a measurement range of 200 mm x 200 mm x 45 mm, uses a diamond stylus tool with a tip radius size of 2  $\mu\text{m}$  to scan the surface. The accuracy over the measurement range is 100 nm in X,Y directions, with a repeatability of 50 nm. The probe measurement accuracy depends on the slope of the object. For slopes up to 30° the accuracy of the installed UA3P is assumed to be below 50 nm.

Since the piecewise differentiable surface topology is not programmable in the UA3P proprietary software, the profilometer is used to scan the surface only. The exported point cloud, representing the center points of the contact probe with a radius of 2.02  $\mu\text{m}$  on the surface, is fitted and recalculated to obtain the shape error image as shown in figure 6. The surface slopes for the radius correction of the diamond stylus are calculated using the design data of the free-form lens array.

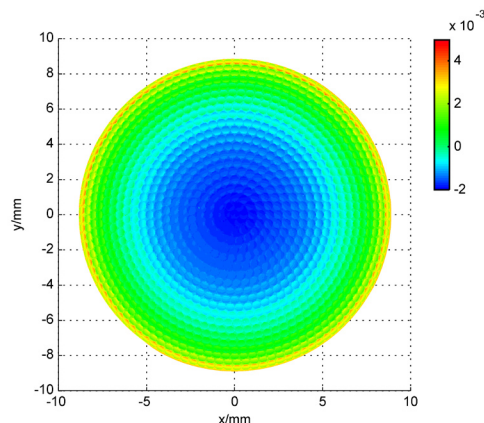


FIGURE 6. Form deviation of the free-form machined micro lens array 1.37  $\mu\text{m}$  (rms).

The shape of this high frequency free-form surface deviates well below  $\pm 3 \mu\text{m}$  (p-v) from the design surface. The measured shape error is 1.37 nm (rms). Visible is a slight radius error of the overall sphere, whose origin is an inaccuracy of the radius value during the toolsetting.

The influence of the inertia of the FTS system is visible in the high-frequency deviations in a lenslets on the outer diameter of the array, where the displacement of the FTS changes with the highest frequency. Here the FTS system overshoots up to 150 nm with a spatial frequency of

100  $\text{mm}^{-1}$  in the areas near the lenslet edges. The frequency and the amplitudes are increased compared to the paraxial area of the lens array. An adjustment of the cutting speeds and feeds in these areas leads to a reduced form deviation.

The surface deviation, measured with the Zygo White Light Interferometer is shown in figure 7. Visible is the deviation of the measured surface from a sphere. The image is a section of a lenslet on the outer diameter of the array. It shows the boundary of that lenslet. The profile in figure 7 shows the cross section through that surface deviation.

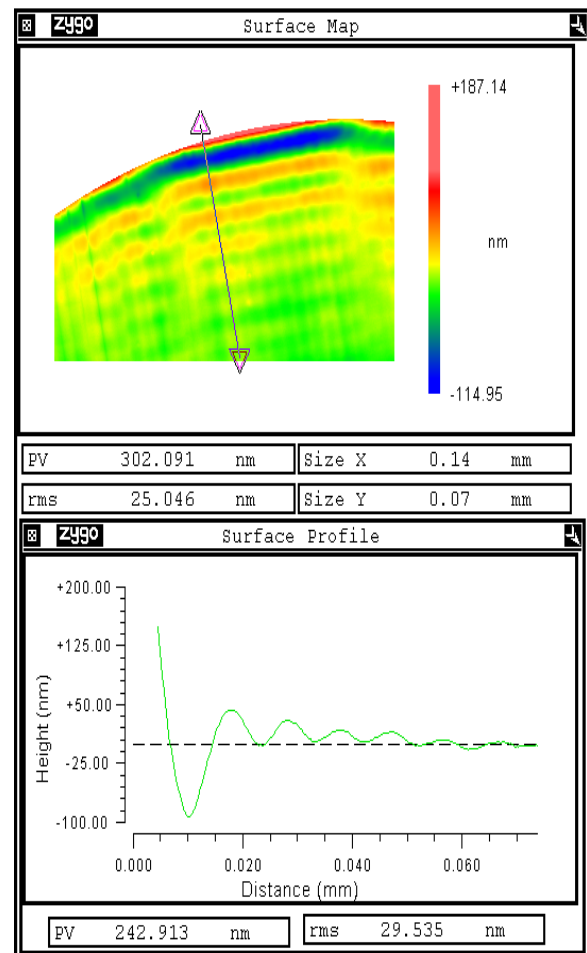


FIGURE 7. Surface deviation from the spherical surface inside a lenslet on the outer diameter of the array shows the kinematic behavior of the FTS system.



## CONCLUSION

Free-form machining using a FTS is demanding regarding the tool path programming, but 3D free-form geometries that are difficult or impossible to manufacture using other technologies can be machined. The FTS used is expedient for machining high frequency free-form surfaces with a size smaller than diameter 50 mm. The reason for this drawback is the amount of data necessary to describe the array in the look up table. An uniform polar meshing with a sufficiently dense point spacing of less than 10  $\mu\text{m}$  raises the computing and loading times significantly.

The processing time of only 80 minutes for the machining of the described high strength Aluminum alloy injection-mold insert and the surface quality of 4 nm (rms) show the good applicability of the free-form machining process for structuring of these small free-form optics. The shape deviation in the  $\mu\text{m}$ -range could be considered functional for infrared imaging optics and for a broad spectrum of illumination optics. Correction cycles to improve the shape of the optical element after a metrology step are not targeted for high frequency free-form surfaces, because the major contributions to the shape irregularities are caused by the inertia of the FTS system and inconsistent cutting conditions over the diameter of the workpiece.

Feasible geometries are mainly limited by the diamond cutting tool geometry with a clearance angle up to  $40^\circ$  and the radius of the diamond tool used. Replication by injection molding opens up the possibility to efficiently and economically reproduce these geometries. The free-form machining can realize its full potential as an adequate addition to lithography for structuring three-dimensional optics in the mesoscopic scale.

## ACKNOWLEDGMENTS

The authors acknowledge the financial support by the Fraunhofer Society that enabled the collaboration between the Fraunhofer Institute for Applied Optics and Precision Engineering (IOF) and the Ohio State University, Industrial and Systems Engineering in the Fraunhofer program Prof  $X^2$ .

This material is partially based on work supported by National Science Foundation under Grant No. CMMI-0928521. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.



*FIGURE 8. Free-form lens array mold insert containing 1,219 single spherical lenslets whose vertices are arranged on a curved surface*

## REFERENCES

- [1] Davis GE, Roblee JW, Hedges AR. Comparison of freeform manufacturing techniques in the production of monolithic lens arrays. vol. 7426. SPIE; 2009. p. 742605.
- [2] Moore Nanotechnology Systems, LLC. NFTS-6000 Specification Overview; 2007. Sales@nanotechs.com. Product Brochure.
- [3] Li L, Yi AY. Microfabrication on a curved surface using 3D microlens array projection. Journal of Micromechanics and Microengineering. 2009;19(10):105010.

# PRECISION MACHINING OF NON-AXISYMMETRIC ASPHERIC GLASS LENS MOLD WITH MICRO FRESNEL STRUCTURES

Shingo Yamamoto<sup>1</sup>, Minoru Hirano<sup>2</sup>, Keiichi Nakamoto<sup>1</sup>,  
Tohru Ishida<sup>1</sup>, and Yoshimi Takeuchi<sup>1</sup>

<sup>1</sup>Department of Mechanical Engineering  
Osaka University

Suita, Osaka, 565-0871 Japan

<sup>2</sup>Research & Department Center  
JTEKT Corporation

Kariya, Aichi, 448-8652 Japan

## INTRODUCTION

In recent years, the demand of optical devices with complicated and accurate shape such as Fresnel lens, optical disk pickup lens and f- $\theta$  lens is growing up in terms of miniaturization and improvement of information equipments. The material for these complicated lenses is almost plastic since the metal dies for plastic lenses can be easily made at comparatively low cost. However, glass lenses, which surpass plastic ones in optical and thermal properties, are required for highly accurate optical systems. Hard and brittle properties are required to die material for glass lenses such as tungsten carbide, ceramics and silicon carbide in order to endure high temperature forming process. Therefore, it is required to develop the highly accurate machining technology of complicated shape for hard and brittle materials.

To meet the requirement, a method to obtain Fresnel shape was proposed, where a grinding wheel with a sharp edge is 2-axis controlled on an axisymmetric surface [1], as shown in Fig. 1. Thus, the study proposes a highly accurate grinding method for glass lens forming dies of cemented tungsten carbide with Fresnel grooves on non-axisymmetric aspheric surface, which is more difficult to create.

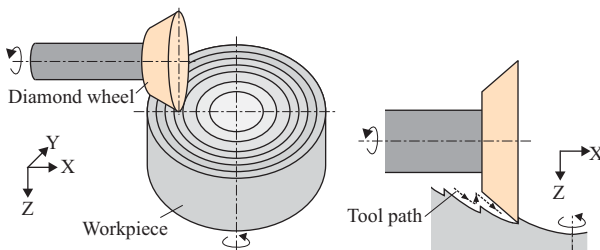


FIGURE 1. Grinding of axisymmetric surface with Fresnel shape

## NON-AXISYMMETRIC ASPHERIC SURFACE GRINDING

### Ground Surface Creation

The shape to be created consists of Fresnel grooves with elliptic zone on non-axisymmetric aspheric surface, as illustrated in Fig. 2. The non-axisymmetric aspheric surface as a basis is defined by some aspheric equation,  $z=f(x, y)$ , and its difference of altitude is about 1.4 mm. In addition, the depth of Fresnel groove is 5  $\mu\text{m}$ . Thus, the positioning accuracy is essential in making grooves on the non-axisymmetric aspheric surface.

The grinding path of the surface shown in Fig. 2 is usually generated with 3-axis control along or perpendicularly to the longitudinal direction of the workpiece surface (X-Y plane), as illustrated in Fig. 3 [2]. However, when there is the positioning error with regard to X-Y plane in

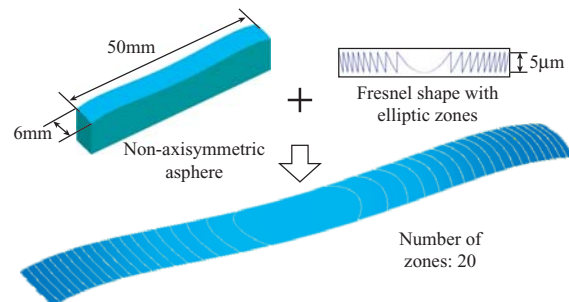


FIGURE 2. Target die shape

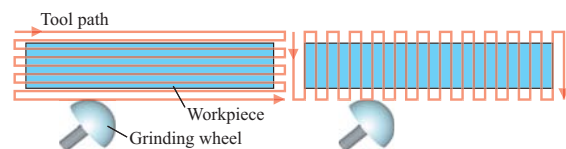


FIGURE 3. Conventional tool path

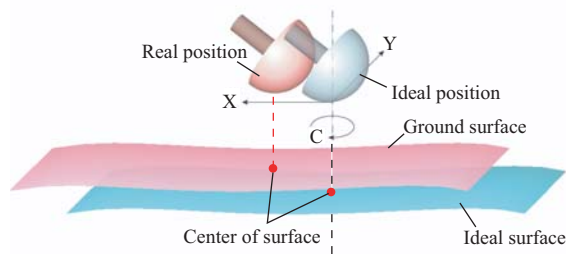


FIGURE 4. Influence of grinding wheel position to the surface

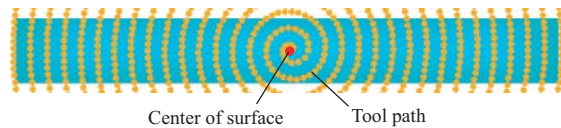


FIGURE 5. Newly proposed spiral grinding path

setting a grinding tool, the real ground surface is formed in the shifted position from the ideal one by the mount of the setting error, as shown in Fig. 4. In addition, Fresnel shape grooving on the ground surface requires 4-axis control grinding, that is, three translational axes and a rotational axis of an ultraprecision machining center. If there is some difference between the center of the rotational axis and that of the ground surface, Fresnel shape may not be created correctly. According to the calculated result, the amount of the difference of several  $\mu\text{m}$  does not allow for the creation of Fresnel groove of  $5\ \mu\text{m}$  in depth.

Thus, 4-axis control spiral grinding tool path by means of the rotational axis of the machining center is applied to grind the non-axisymmetric aspheric surface in the study since the grinding method makes it easy to match the ground surface to the ideal one in case of removing the workpiece from the table and mounting it again.

#### Generation of Grinding NC Data

Grinding NC data is generated so that the grinding points with the same pitch can move along a spiral path, using the polar coordinate system in place of Archimedes spiral, as illustrated in Fig. 5. When the pitch is given, the coordinates (X, Y) of the grinding point are obtained, and the Z coordinate is calculated by use of the aspheric surface equation. The grinding tool center position can be obtained on the basis of the normal vector from the grinding point and the grinding wheel radius.

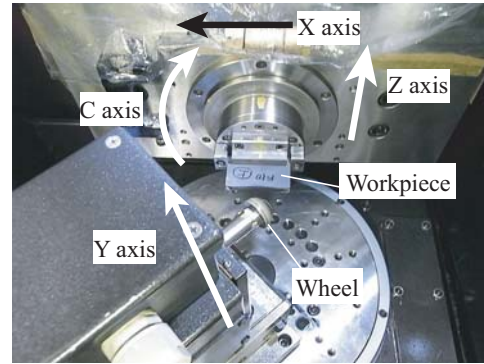


FIGURE 6. Setup for surface grinding

TABLE 1. Grinding conditions of non-axisymmetric asphere

| Workpiece                 | Binderless tungsten carbide F10 (FUJI DIE CO.,LTD) |
|---------------------------|----------------------------------------------------|
| Wheel                     | SD3000P150BPF                                      |
| Rotational diameter       | $\phi 25\ \text{mm}$                               |
| Rotational rate           | 12000 rpm                                          |
| Depth of cut (Rough cut)  | $2\ \mu\text{m}$                                   |
| Depth of cut (Finish cut) | $1\ \mu\text{m}$                                   |
| Feed rate                 | 200 mm/min                                         |
| Grinding fluid            | Oil mist                                           |



FIGURE 7. Ground workpiece

#### Compensation Grinding

Then, the surface measurement is performed to obtain the shape error data by use of a measuring instrument (UA3P: Panasonic). The surface of the workpiece demounted from C-axis table is measured by repeating the measurement in the longitudinal direction. The shape error stands for the difference between the aspheric surface equation and the measured Z coordinate value. The shape error data is used in compensation grinding, however it is impossible to correspond grinding points with measuring points. Thus, the measured data is interpolated for compensation grinding.

The interpolation is performed by use of cubic spline curve after smoothing the moving-averaged data in every scanned line, which enables to calculate the shape error  $Z_{\text{error}}$  at any point on the aspheric surface. In compensation of grinding NC data, the compensated Z coordinate value  $Z_{\text{comp}}$  is given by  $Z - Z_{\text{error}}$ .

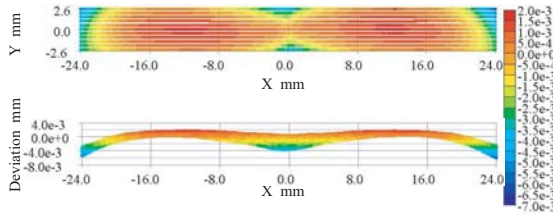
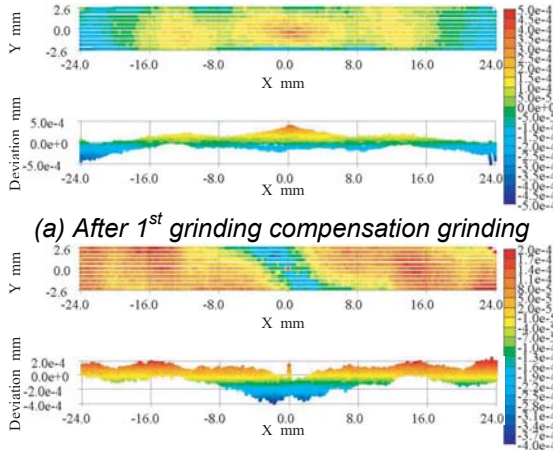


FIGURE 8. Shape accuracy after grinding

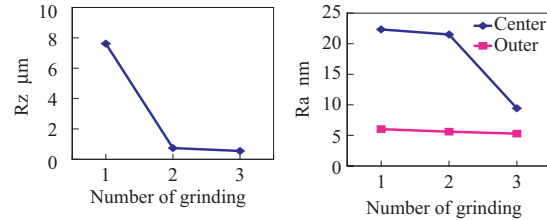


(a) After 1<sup>st</sup> grinding compensation grinding  
(b) After 2<sup>nd</sup> grinding compensation grinding  
FIGURE 9. Improvement of shape accuracy

#### Non-axisymmetric Aspheric Surface Grinding

A grinding experiment is performed to create the non-axisymmetric aspheric surface by applying the proposed grinding method. The workpiece material is a tungsten carbide, and the grinding wheel is a spherical resinoid bonded diamond wheel. The workpiece is mounted to the ultraprecision machining center (AHN05: JTEKT Co.), as shown in Fig. 6. The grinding condition is listed in Table 1. The ground workpiece is shown in Fig. 7. It takes about 7 hours in completing the grinding. The shape accuracy of the ground surface is  $7.62 \mu\text{m}$  (P-V), as shown in Fig. 8.

Based on the measured shape error data, the compensation grinding is performed. The shape accuracy measured after the first compensation grinding is shown in Fig. 9(a) and that after the second compensation grinding in Fig. 9(b). From these figures, the change in the shape accuracy is plotted in Fig. 10(a), which demonstrates the remarkable improvement of the shape accuracy. In addition, the surface roughness of the center area and the outer area is observed by use of a microscope (New View 5022: Zygo). They are  $9.4 \mu\text{m}$  (Ra) and  $5.2 \mu\text{m}$  (Ra) respectively, as shown in Fig. 10(b). It is seen that the compensation grinding can improve both the shape accuracy and the surface roughness.



(a) Shape accuracy (b) Surface roughness

FIGURE 10. Improvement of shape accuracy and surface roughness by the number of compensation grinding

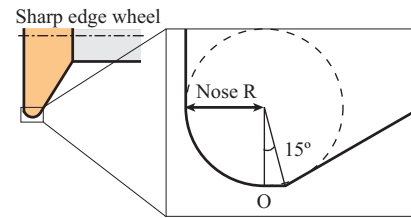
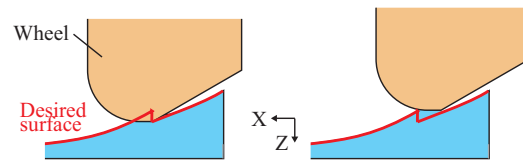


FIGURE 11. Grinding wheel model



(a) Without compensation (b) With compensation  
FIGURE 12. Cause of shape error

#### GROOVE GRINDING ON NON-AXISYMMETRIC ASPHERIC SURFACE Fresnel Shape Grinding Method

A disk type metal bonded diamond wheel with a sharp edge of 60 degree is used to create Fresnel shape on non-axisymmetric aspheric surface. The grinding wheel is suitable for a small depth of cut due to the small amount of elastic deformation [3]. In grinding, it is difficult to form a sharp edge or corner. Thus, the grinding wheel with some radius at the top edge is defined as its model in generating grinding NC data, as illustrated in Fig. 11. This is because a position difference may take place, as illustrated in Fig. 12, if the grinding operation is performed without considering the top edge roundness, in setting the grinding wheel, the point O of the model is adjusted so as to correspond with the origin of X, Y and Z machine coordinates.

#### Generation of Groove Grinding NC data

Since Fresnel shape is elliptic, the elliptic grinding points are prepared, and the grinding wheel should be directed to a grinding point M at the angle  $\beta$  so that the wheel can make contact



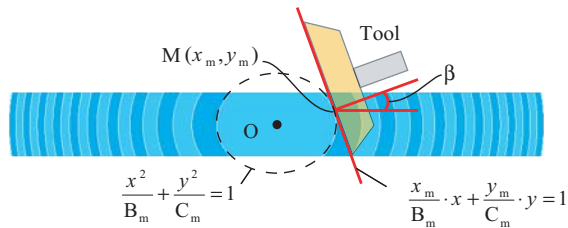


FIGURE 13. Setting of grinding wheel by C axis

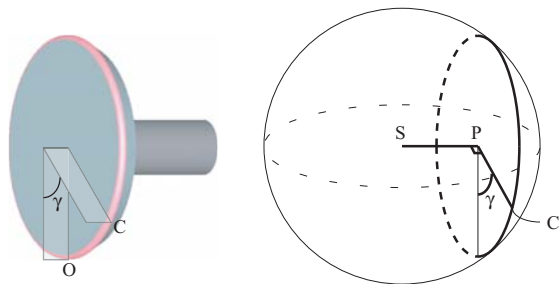


FIGURE 14. Contact angle with Fresnel groove

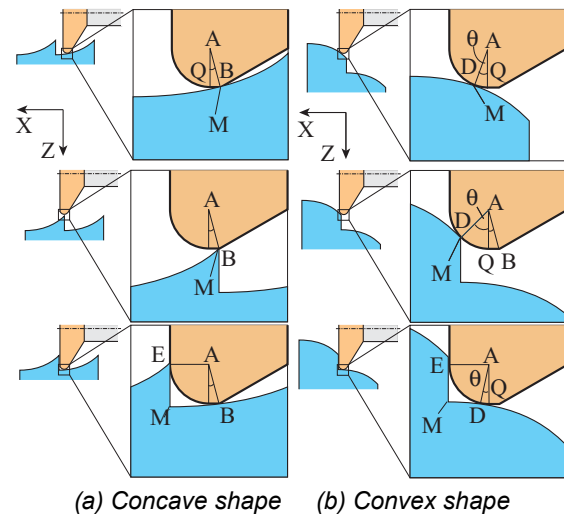


FIGURE 15. Contact point with grinding wheel

tangentially with it by rotating C axis, as illustrated in Fig. 13. In addition, the angle  $\gamma$  at the contact point C is obtained from such a contact relationship as shown in Fig. 14. At the time, the contact point with the grinding wheel at the point M corresponds to the point B in case of the concave surface shown in Fig. 15(a) and to the point D in case of the convex surface shown in Fig. 15(b). Then, the coordinate of the grinding wheel center point can be determined, which leads to the generation of NC data. The grinding path is generated from the first Fresnel groove ring at the center to the 21st one at the outside.

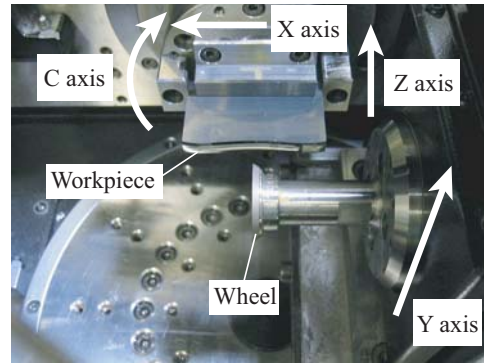


FIGURE 16. Setup of Fresnel groove grinding

TABLE 2. Fresnel grinding conditions

|                           |                                                    |
|---------------------------|----------------------------------------------------|
| Workpiece                 | Binderless tungsten carbide F10 (FUJI DIE CO.,LTD) |
| Wheel                     | SD3000I75M40                                       |
| Rotational diameter       | φ25 mm                                             |
| Rotational rate           | 12000 rpm                                          |
| Depth of cut (Rough cut)  | 2 μm                                               |
| Depth of cut (Finish cut) | 1 μm                                               |
| Feed rate                 | 80 mm/min                                          |
| Grinding fluid            | Oil mist                                           |



FIGURE 17. Fresnel ground workpiece

### Fresnel Shape Grinding

The setup of Fresnel shape grinding is shown in Fig. 16. The top edge roundness of the disk type metal bonded diamond wheel obtained by carbon transcribed grinding is 2 μm, which is considered to generate NC data. The groove grinding condition is listed in Table 2. The ground Fresnel shape is shown in Fig. 17. It takes about 17 hours to finish it. The carbon transcribed top edge roundness after Fresnel grinding is about 55 μm, which is remarkably large.

Figure 18 is Fresnel groove shape obtained by subtracting the non-axisymmetric aspheric surface from the measured shape data. It is seen that Fresnel shape is well created on the non-axisymmetric aspheric surface. However, according to the comparison of the designed groove and the measured one with regard to the first and 18th Fresnel groove, it is seen that there are remainings not to be ground due to the

top edge roundness and shifted groove positions of 10 to 15  $\mu\text{m}$  due to the setting error in exchanging grinding wheels and due to the wear and deformation of grinding wheel, as shown in Fig. 19.

## CONCLUSION

The study proposes a new grinding method of non-axisymmetric aspheric cemented tungsten carbide mold with micro Fresnel shape with high accuracy. The study is summarized in the following.

- (1) NC data with a spiral path is developed to grind non-axisymmetric aspheric surfaces, and the compensation grinding program is also successfully developed, based on the measured shape data interpolated by cubic spline.
- (2) Micro Fresnel shape grinding NC data is generated on non-axisymmetric aspheric surfaces with a disk type metal bonded diamond wheel. As a result, it is found that micro Fresnel shape is created on the surface with the difference of altitude of 1.4 mm.

## REFERENCES

- [1] Yamamoto Y, Suzuki H, Moriwaki T, Okino T, Higushi T. Precision Grinding of Micro Fresnel Lens Molding Die (2nd Report) Precision Truing of Micro Grinding Wheel with Sharp Edge by Molybdenum Truer and Accuracy Improvement in Fresnel Surface Grinding. Journal of the Japan Society for Precision Engineering. 2007, 73:6 688-692. (in Japanese)

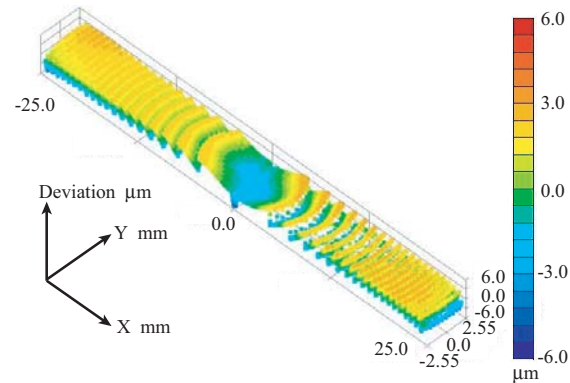
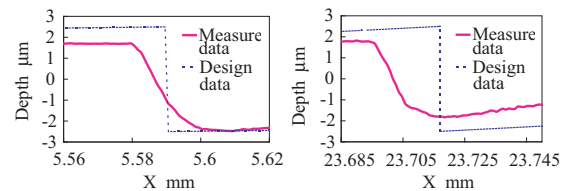


FIGURE 18. Measured Fresnel shape



(a) 1st groove edge (b) 18th groove edge

FIGURE 19. Fresnel groove edge profile

- [2] Kuriyagawa T, Tachibana T, Shoji K, Mori Y. Nonaxisymmetric Aspheric Ceramic Mirror Machining Using Arc Envelope Grinding Method. Journal of the Japan Society of Mechanical Engineering Series C. 1997; 63:611 2532-2537. (in Japanese)
- [3] Yamamoto S, Fujii T, Hirano M, Shibukawa T, Ishida T, Takeuchi Y. Machining of Glass Lens Mold with Minute Structures by Grinding and Cutting. Proc. of 23th ASPE Annual Meeting. 2008; 640-643.



# DIAMOND MICRO CHISELING OF LARGE-SCALE RETROREFLECTIVE ARRAYS

Ekkard Brinksmeier<sup>1</sup>, Lars Schönmeyer<sup>1</sup>, Ralf Gläbe<sup>1</sup> and Simon Weingärtner<sup>2</sup>

<sup>1</sup>LFM – Laboratory for Precision Machining

Bremen University, Germany

<sup>2</sup>IMOS Gubela GmbH

Renchen, Germany

## INTRODUCTION

Retroreflective surfaces are functional features for safety applications, communications and measurement equipment. They can be machined as a combination of lens and mirror (cat's-eye retroreflector) or in the form of triple mirrors [1]. The latter are called cube corner retroreflectors because they consist of three perpendicular mirror facets with triangular or hexagonal aperture [2]. In most applications, multiple of these structures are combined in an array to form a retroreflecting surface. In this paper, the term hexagonal or triangular retroreflector describes an array of the above-mentioned triple mirror structures.

Reducing the structure size of hexagonal retroreflectors is of particular interest, as they provide a 33 % higher efficiency compared to triangular retroreflectors (see FIGURE 1) [3].

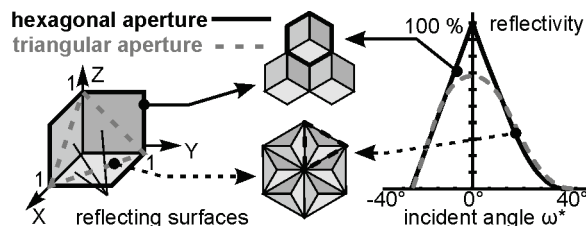


FIGURE 1: Reflectivity of retroreflectors with hexagonal and triangular aperture cf. [3].

Furthermore, when replicating an array of miniaturized structures on reflective foils, the retroreflective surface can be bent without loss of optical function and thus offer a broader range of possible applications. Additionally, smaller structures result in a lower parallel displacement of the reflected light and thereby allow smaller measurement devices and improved results.

While a downscaling of structure size is possible for arrays of triangular retroreflectors using diamond milling or grooving [4] processes, this is a challenging task for hexagonal retroreflector-arrays, due to the absence of continuous tool paths. In this case, the concave sharp edges cannot be machined by processes based on rotational motions (e.g. turning or milling) [5].

## DIAMOND MICRO CHISELING

The Diamond Micro Chiseling (DMC) process has been developed to machine sharp-edged pyramidal microcavities in a size between 50 and 500  $\mu\text{m}$ , thus enabling the generation of miniaturized hexagonal retroreflector-arrays [6].

### Tool geometry

The DMC process relies on dedicated V-shaped monocrystalline diamond tools. In comparison to conventional diamond tools used for turning or milling operations, the DMC tools are utilized 90° rotated around the shaft axis while maintaining the cutting direction of conventional tools. This results in a switched alignment of rake and flank face and consequently a completely different configuration of the cutting edges and tool angles. The characteristics of the diamond tools used for Diamond Micro Chiseling are shown in FIGURE 2.

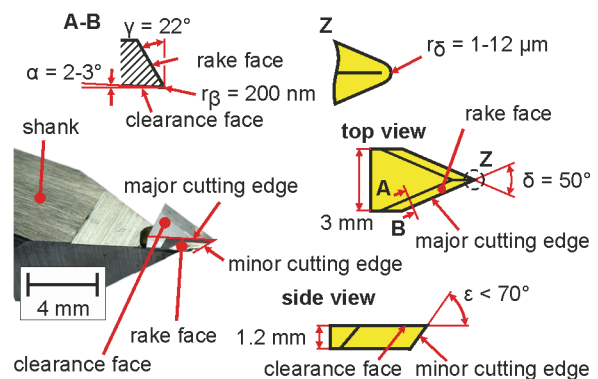


FIGURE 2: V-shaped diamond tool dedicated for the Diamond Micro Chiseling process.

Most notably, the tools feature a rounded nose ( $r_\delta = 1-12 \mu\text{m}$ ) as well as intrinsic rake ( $\gamma = 22^\circ$ ) and clearance ( $\alpha = 2-3^\circ$ ) angles. The opening angle ( $\delta = 50^\circ$ ) and the corner angle ( $\epsilon = 70^\circ$ ) of the tool determine the machinable geometric spectrum of the microcavities. Some DMC tools also feature a rounded cutting edge ( $r_\beta = 200-300 \text{ nm}$ ), which improves the overall stability of the tool and is mainly used for rough cutting purposes.

### Machine setup and process kinematics

An ultraprecision machine tool with at least five numerically controlled axes (three linear and two rotational) is required for the Diamond Micro Chiseling process (see FIGURE 3).

One of the rotational axes (B) is used for setting the inclination angle ( $\chi$ ) of the tool relative to the workpiece, while the second one (C) is used to rotate the workpiece itself. The linear axes (X, Y and Z) are used for positioning the tool relative to the workpiece and for executing the cutting motion.

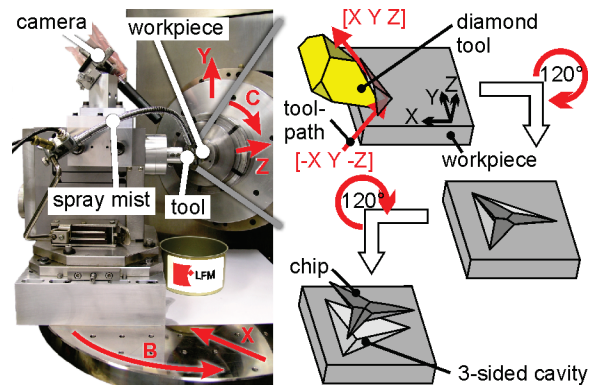


FIGURE 3: Machine setup and kinematics for Diamond Micro Chiseling

In the first step, the tool plunges into the surface in  $[-X Y -Z]$  direction until the apex of the cavity is reached and is then retracted from the surface in  $[X Y Z]$  direction. Hence, a single mirror facet with triangular geometry is created which has an inclination angle equal to  $\chi$ . For cutting the next facet, the workpiece has to be rotated and the tool repositioned to the endpoint of the previous cut. This procedure is continued until the starting point of the first cut is reached and the chip is separated from the cavity.

In to minimize the stress on the diamond tool, the structures have to be cut in several layers with constant chip thickness [7]. Therefore, a stack of the same cavity is machined with decreasing offset in Z direction.

### Tool alignment

As the chip is only separated from the cavity if the boundaries of the individual cuts meet with a high accuracy, the precise alignment of the tool is crucial to the success of the process.

The alignment procedure is divided into four steps which need to be repeated in an iterative cycle until the desired form accuracy is reached. In the first step, the tool is aligned parallel to the YZ-plane of the machine in order to be able to

set the inclination angle ( $\chi$ ) of the tool using the B-axis.

In the second step, the contact point between tooltip and workpiece has to be determined by adjusting the Z-position of the tool. This is necessary as the depth of cut influences the stress on the diamond and also the form accuracy (depth and width) of the cavity structures. A coarse alignment is done by observing the tooltip and its reflection on the workpiece using the camera system shown in FIGURE 3. The Z-position is then corrected by moving to tool towards the surface in discrete steps until cutting marks can be observed (see FIGURE 4). According to the number of cutting marks and the moved steps, it is possible to set the Z-position of the tool with an accuracy in the range of the step size, which usually is 250 nm.

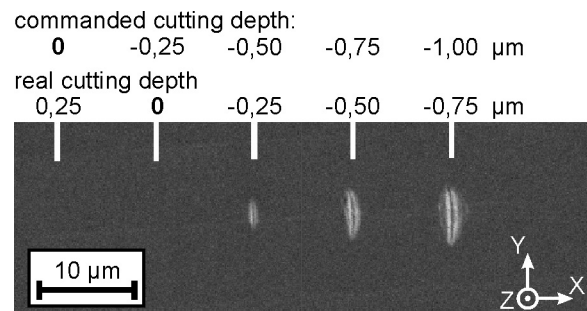


FIGURE 4: Cutting depth alignment of the diamond tool using discrete cutting marks

The third step is concerned with aligning the diamond tool to the rotational center (C-axis) of the main spindle. For this, dedicated alignment structures have been developed, consisting of two symmetric parts, which ideally form a square (see FIGURE 5). In Y-direction, a continuous cut can be machined, as it coincides with the intended cutting direction of the tool. In X-direction, discrete cutting marks, comparable to those of the Z-alignment, have to be machined and interpolated to a line during measurement.

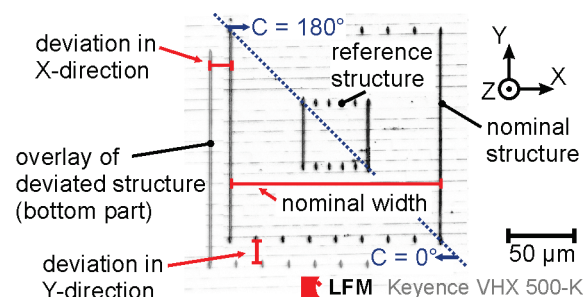


FIGURE 5: Alignment structure for XY-positioning of the DMC diamond tool

One L-shaped half of this square is machined at zero rotation of the C-axis. A second L-shaped half is machined at a fixed distance to the first as a reference for automated measurements. The other halves of the squares are machined after rotating the C-axis by 180° and repositioning of the tool to the expected position of the first halves. If the tool is not precisely aligned on the rotational center, the resulting squares are deformed. Their deviation is measured using a calibrated video microscope and used for compensating the tool's position.

In the last step, cavities are machined into the workpiece using the DMC process. These are evaluated for dimensional and angular accuracy and if necessary, the inclination angle of the tool is corrected. Due to deviations in positioning the tooltip on the rotational center of the B-axis (this error cannot be compensated by moving the machine's axes) the whole alignment procedure has to be repeated until the desired values for the inclination angle are reached.

### Process performance

For evaluating the performance of the DMC process, groove type structures have been machined in different workpiece materials while varying the undeformed chip thickness and the cutting speed of the process. Electroless nickel (NiP) and nickel silver N37 (CuNi18Zn19Pb1) have been proven to yield an optical surface finish within the set of applicable process parameters (see FIGURE 6) [8].

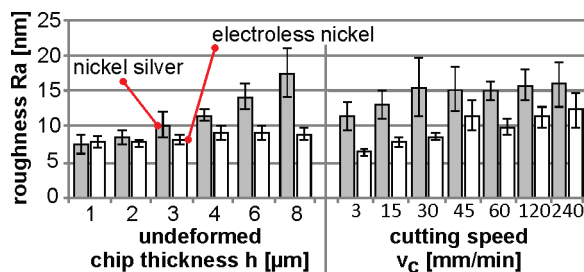


FIGURE 6: Surface roughness  $R_a$  against undeformed chip thickness (left) and cutting speed (right) for different workpiece materials cf. [8].

However, only nickel silver is suitable for large-scale retroreflective arrays as it results in significantly lower tool wear, compared to electroless nickel.

### CUTTING STRATEGIES FOR LARGE-SCALE RETROREFLECTIVE ARRAYS

Triple mirrors require a three-sided cavity with an inclination angle of  $\chi = 54.7356^\circ$ . When

machining multiple of these cavities in an overlapping fashion, a hexagonal cube corner is obtained (FIGURE 7).

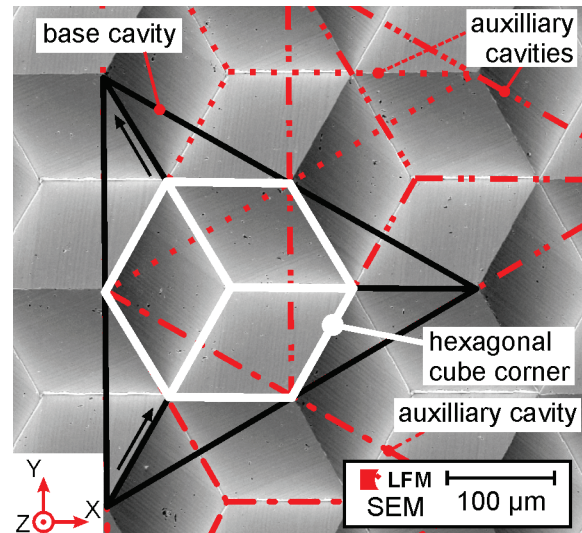


FIGURE 7: Cutting cube corner retroreflectors using DMC by overlapping 4 triangular cavities.

In practice, cutting each of the three-sided cavities separately and in multiple layers quickly results in process times of several days. For example, Diamond Micro Chiseling a 5 x 5 mm<sup>2</sup> array with a characteristic structure dimension of 150 μm (i.e. 1216 structures) using an undeformed chip thickness of  $h = 4$  μm results in 69312 discrete cuts. At a maximum cutting speed of  $v_c = 60$  mm/min this sums up to a process time of around 50 h. During this time, the cutting conditions have to be monitored and the machine tool and its environment have to be kept as stable as possible.

Industrial applications, however, require the structuring of areas which are significantly larger than at least 10 x 10 mm<sup>2</sup>. This is a 'large' area in terms of the amount of structures and thus the required machining time. Hence, dedicated cutting strategies have to be applied to enable a feasible structuring of such surfaces:

1. Reduction of workpiece rotations and thus tool repositioning time by concatenating cuts with the same orientation.
2. Minimization of the toolpath by changing the simple "stacking" of cavities to cutting individually sized cavities for each layer.
3. Truncation of adjacent cuts by connecting their intersection points and omitting non-essential motions.
4. Performance of in-situ tool changes to divide between rough cutting with large

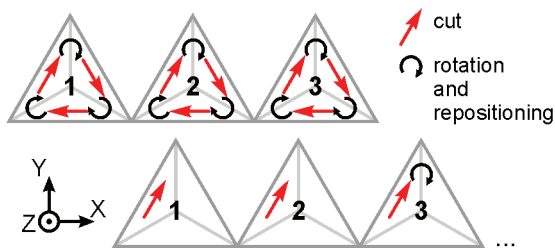


undeformed chip thickness/high cutting speed and finish cutting with finer tools and quality oriented machining parameters.

5. Reduction of non-productive process time by utilizing semi-automated tool alignment procedures.
6. Improvement of machine stability and control behavior for minimizing vibrations induced by changes of speed and direction at the corners of the discontinuous tool path.

The ideas of strategies 1 to 3 include more or less simple geometric calculations and strategies for sorting the individual cuts which are illustrated in FIGURE 8, but will not be discussed here in detail.

#### Strategy 1: optimization of cutting sequence



#### Strategy 2: individually sized cavities



#### Strategy 3: cutting path truncation



FIGURE 8: Truncation of DMC tool path to minimize non-productive movement of the tool

By performing an in-situ tool change, as stated in point 4, different tools can be utilized for rough and finish cutting. Thus, rough cutting tools are optimized for high material removal rates by applying a comparably large nose radius as well as a rounded cutting edge, in order to prevent chipping while applying a high undeformed chip thickness. Finishing tools, on the other hand, are optimized for contouring accuracy and optimum surface roughness and are only used for machining the bottom 'layers' of the cavity.

An in-situ tool change, however, always implies a new tool alignment which is time consuming and introduces additional uncertainties into the process: The novel tool has to be precisely aligned to the angular and lateral position of the

previous tool or else the structuring process cannot be continued within the already machined cavities. This has to be done within the range of the undeformed chip thickness applied for the finishing layers (1-3  $\mu\text{m}$ ).

Several attempts have been made to improve the accuracy and speed of the tool alignment procedure. Using a telecentric lens system and a CCD-camera, it was possible to calculate the tool correction factors using image recognition techniques on the alignment structures shown in FIGURE 5. In initial experiments, setting the deviation of the alignment structures to known values, the correction factors could be calculated with a repeatability of  $<1 \mu\text{m}$  in minimal time.

### EXPERIMENTAL RESULTS

Using optimization strategies one, four and six described above, it was possible to machine a highly efficient retroreflective array with a structure size of  $200 \mu\text{m}$  covering an area of  $10 \times 10 \text{ mm}^2$ .

At first, a rough cut, using a  $r_\delta = 12 \mu\text{m}$  tool with rounded cutting edge was used. After cutting 18 layers with  $h = 5 \mu\text{m}$  and  $v_c = 45 \text{ mm/min}$ , a tool change to a  $r_\delta = 1 \mu\text{m}$ , sharp edged diamond tool was performed. The finish cut was done in three layers ( $h = 2 \mu\text{m}$ ;  $1.28 \mu\text{m}$  and  $1 \mu\text{m}$ ) with  $v_c = 15 \text{ mm/min}$ .

The total process time was approx. 200 hours, including the times for alignment of the above-mentioned diamond tools.

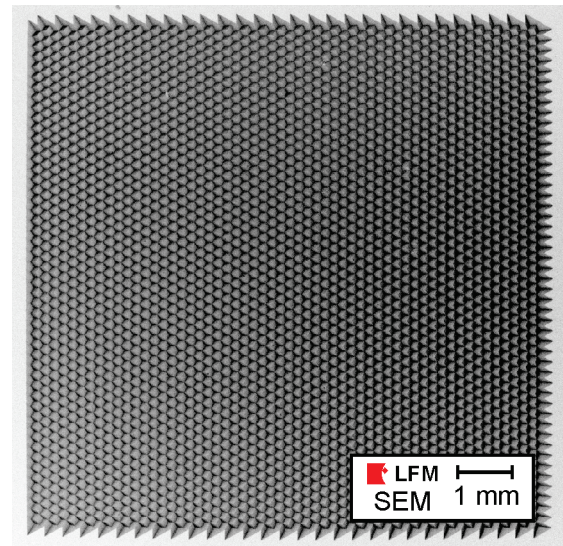
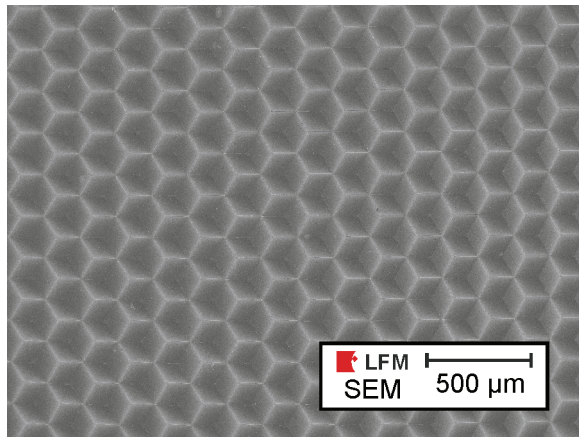


FIGURE 9: Overview of  $10 \times 10 \text{ mm}^2$  cube corner array with a structure size of  $200 \mu\text{m}$ .

The SEM images depicted in FIGURE 9 and FIGURE 10 show, that a homogenous optical quality was achieved across the entire surface.



**FIGURE 10:** Close-up view of the 10 x 10 mm<sup>2</sup> cube corner array.

For evaluating the optical performance of the retroreflective surface, the cube corner array was measured using a reflection measurement system. This system illuminates the sample from different angular positions and measures the luminance intensity.

According to these measurements, the relative angular deviation of the cube corner facets was calculated to 0.1°. The overall luminance intensity was up to 50% higher than comparable structures with triangular geometry.

## CONCLUSION AND OUTLOOK

In this paper, the latest results of micro-retroreflectors machined by DMC have been presented. The achievable surface quality and form accuracy was presented as well as first results for measuring the optical functionality of the array. Particular attention was given to the measurement procedures for the alignment of the diamond tool within the ultraprecision machine tool. Furthermore, specific strategies for minimizing the required machining time were presented.

The ongoing research focuses on further reduction of process times by implementing the machining strategies 2 and 3, as well as speeding up the tool alignment process using image recognition techniques. Another focus lies on improving the B-axis alignment procedure for obtaining more accurate structure angles and thus a higher efficiency of the machined cube corner arrays.

## ACKNOWLEDGEMENT

The authors like to thank the German Research Foundation (DFG) for funding this work as a part of the Transregional Collaborative Research Center SFB/TR4 "Process Chains for the Replication of Complex Optical Elements".

## REFERENCES

- [1] Liepmann TW. How retroreflectors bring the light back. *Laser Focus World*. 1994 Okt;30(10):129.
- [2] Seward GH, Cort PS. Measurement and characterization of angular reflectance for cube-corners and microspheres. *Optical Engineering*. 1999;38(1):164-169.
- [3] Autschbach L, Brinksmeier E, Gubela H, Ahbe T. Manufacturing of three-dimensional micro-optic functional surfaces. *HTM - Journal of Heat Treatment and Materials*. 2005;1:33-39. German.
- [4] Moriya T, Nakamoto K, Ishida T, Takeuchi Y. Creation of V-shaped microgrooves with flat-ends by 6-axis control ultraprecision machining. *CIRP Annals - Manufacturing Technology*. 2010;59(1):61-66.
- [5] Denkena B, Boehnke D, Kästner J. Microstructuring of functional surfaces by means of cutting processes. *Prod. Eng. Res. Devel*. 2008 2;2(1):21-25.
- [6] Brinksmeier E, Gläbe R, Flucke C. Manufacturing of molds for replication of micro cube corner retroreflectors. *Prod. Eng. Res. Devel*. 2008;2:33-38.
- [7] Flucke C, Gläbe R, Brinksmeier E. Diamond Micro Chiselling of Molding Inserts for Optical Micro Structures. In: *Proceedings of the 23th ASPE Annual Meeting and 12th ICPE*. Portland: 2008. p. 92-95.
- [8] Brinksmeier E, Schönmann L, Gläbe R. Review on Diamond-Machining Processes for the Generation of Functional Surface Structures. In: *Proceedings of the 4th CIRP International Conference on High Performance Cutting*. Gifu, Japan: 2010. p. 79-84.

# METROLOGY WITH A NON-CONTACT PROBE FOR MANUFACTURING FREEFORM OPTICS

Scott DeFisher, Theodore Lambropoulos, Scott T. Bambrick, Shai N. Shafir  
OptiPro Systems

Ontario, New York, United States Of America

## INTRODUCTION

In this work, we present a non-contact measurement method for characterizing complex freeform optical surfaces called UltraSurf. A series of measurements using the UltraSurf have been demonstrated for traditional optical surfaces, such as flats and spheres, in addition to mild to "wild" aspheres and freeforms. Each shape has its own unique challenges and benefits, including complexity of motion path and required number of motion axes. This data serves as the basis for measuring complex freeform shapes such as toroids, ogives, and pure freeforms.

## FREEFORMS

A freeform optic is defined as having an irregular or asymmetrical shape or design. Definitions of freeform surfaces are very important in the manufacturing and metrology of freeforms. An easy to understand definition is required to ensure correct generation of the freeform.

Freeform shapes are commonly generated on multi-axis computer numerically controlled (CNC) optical generating and polishing machines in conjunction with computer aided machining (CAM) software. Therefore, the freeform definition needs to be easily transportable to these programs. Freeform manufacturers also require a surface metrology map that provides the error or deviation from the nominal shape to correct any discrepancies. Metrologists require a definition that is easy to model inside of a computer in order to calculate the error map for the manufacturer. Calculating an error map from the nominal shape requires a numerically stable definition of the freeform.

Common definitions of freeform surfaces include mathematical equations, cloud of points, and computer aided design (CAD) files. The various definitions have individual strengths and weaknesses. Mathematical equations can be a function or summation of basis functions such as radial basis functions [1] or Zernike polynomials. A CAD file is a three dimensional representation

of the freeform in a computerized format consisting of non-uniform rational B-splines. A cloud of points is generally created by sampling a mathematical equation or CAD file at discrete intervals. Generally speaking, the mathematical equation is the most pure definition of the freeform, but can be cumbersome to work with in manufacturing. A CAD file can be imported into CAM software for manufacturing, but can be more difficult to work with on the metrology side. A cloud of points is most compatible metrology, but can suffer from sampling issues and is potentially more difficult to work with in manufacturing. A combination of these definitions will likely be required for manufacturing and metrology until a standard definition for freeforms is created.

## ULTRASURF

The UltraSurf traverses a non-contact probe over the part under test while staying normal to the surface. A description of the part's shape is required and is supplied to the UltraSurf before measurement occurs. Currently, freeform surfaces have no standard definition; therefore, techniques have been developed using point clouds, mathematical equations, and CAD models to communicate the freeform shape to the UltraSurf. Some manual alignment of the part is required for the UltraSurf to maintain the probe's depth of field. Symmetry in the part can be exploited during the alignment and measurement stages for efficiency.

## Mechanical Specifications

UltraSurf uses five air bearing axes and high-resolution positioning scales to scan with a non-contact probe over the part under test (FIGURE 1). The result is non-contact coordinate measuring machine. UltraSurf has five axes of motion to keep the non-contact probe normal to the surface of the freeform. The axes specifications are summarized in TABLE 1. The measurement result is a topographical map. The map is created by converting the machine coordinates and probe data into a cloud of points similarly to a coordinate measuring



machine (CMM). The topographical map can be compared against the ideal freeform shape, creating an error map.

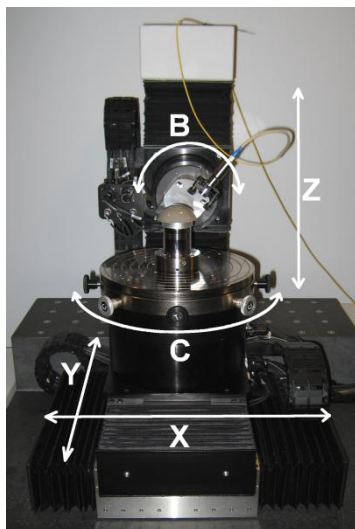


FIGURE 1. Photograph of UltraSurf with labeled axes of motion. Probe moves with B and Z axes, part moves with X,Y,and C axes.

TABLE 1. Specifications for the axes of motion.

| Axis       | X,Y,Z  | B     | C     |
|------------|--------|-------|-------|
| Travel     | 200 mm | 360°  | 360°  |
| Resolution | 5 nm   | 0.02" | 0.01" |

### Non-Contact Probes

Multiple non-contact probes have been installed and tested on the UltraSurf. OptiPro currently measures with two types of probes, but the UltraSurf is not limited only to these. Although each probe shares the ability to read a distance from a reference point, they have unique qualities. The first probe uses low-coherence interferometry (LCI) [2] with a safe, near infrared laser and can measure distance when coupled with an internal reference plate. It is able to read both surfaces and thickness of an optical window at a single point. The second probe uses confocal chromatic sensing (CCS) with white light to measure distance at a single point [3]. It is more accurate than the first probe, but can only measure one surface at a time [4]. Both probes have proven capable of measuring many different optical materials that have rough or fine surface texture. The single point measuring method gives the UltraSurf a large dynamic range, giving it the ability to measure difficult freeform and conformal optics. In addition, OptiPro is currently researching several

other probe technologies to be implemented on the UltraSurf for different metrology applications.

### Metrology Data

A cloud of points is generated after the UltraSurf has finished scanning the part with the non-contact probe. The next step is to match the point cloud with the ideal defined shape (FIGURE 2).The fitting procedure removes any misalignment of the part during the measurement; therefore, meticulous manual alignment is not required. Several published techniques already exist for aligning point clouds to models [5].

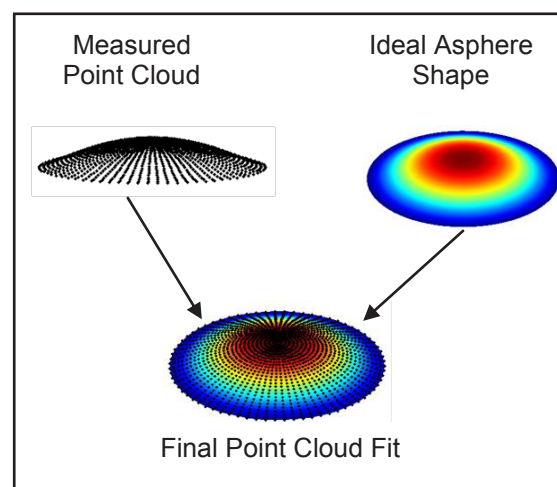


FIGURE 2. Point cloud fitting process.

The definition of the freeform is critical in the fitting stage. The fitting routine can have difficulty solving for the best fit without a stable definition of the freeform. Traditionally, spheres and aspheres have radius tolerances, and these can be incorporated into the fitting to find the best-fit radius. Similarly, if a freeform has a specific tolerance, you can use the definition of its shape to account for it.

The form is then removed after the measured cloud has been fit to the ideal shape. The result is residual error from the best-fit shape. The residuals can be calculated vertically, or normal to the surface. The error map is then interpolated to a grid, to produce a false color image (FIGURE 3) that can be manipulated for feedback into the grinding or polishing process.

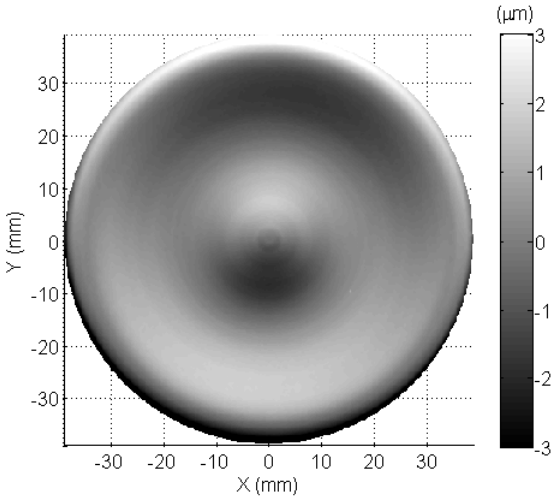


FIGURE 3. False color error map of asphere as measured on UltraSurf

### CURRENT WORK AND RESULTS

OptiPro is developing equipment that is able to grind and polish freeform shapes. Therefore we have has several freeforms for testing with the UltraSurf. The freeforms utilize all five axes of the UltraSurf to generate the point cloud. The non-contact scanning path uses the surface normals calculated from the mathematical equation of the freeform or a cloud of points with a finite difference.

#### Anamorphic Asphere Result

An anamorphic asphere is a non-rotationally symmetric surface. It can have bi-conic curvature in its two orthogonal directions, along with higher order asphere terms. OptiPro performed a quick polish on a specific anamorphic asphere (FIGURE 4), and subsequently measured on UltraSurf (FIGURE 5).



FIGURE 4. Anamorphic asphere, 35mm wide by 50 mm long.

The anamorphic asphere was optimized using the standard equation (EQ.1). This equation allowed for radius fitting in the two conic directions. The resulting error map displays various surface features that could be traced back to either the grinding or polishing stage of manufacturing. The error map can now be used as feedback in a deterministic polishing platform for further correction.

$$Z = \frac{c_x x^2 + c_y y^2}{1 + \sqrt{1 - (1 + k_x)c_x^2 x^2 - (1 + k_y)c_y^2 y^2}} + \sum_{i=1}^N A_{r,i} [(1 - A_{p,i})x^2 + (1 + A_{p,i})y^2]^i \quad (1)$$

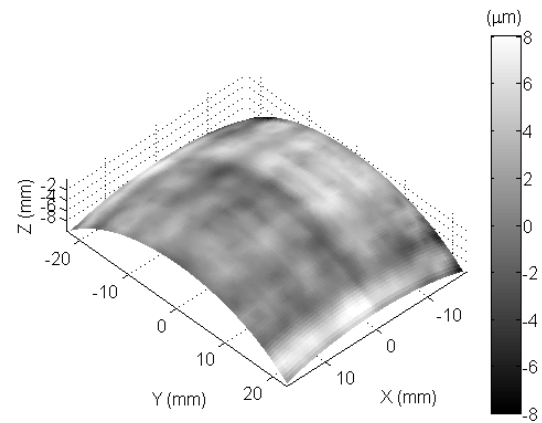


FIGURE 5. Anamorphic asphere error map as measured on UltraSurf

### FUTURE RESEARCH

The main goals for future UltraSurf research revolve around three topics; measuring freeforms, using the measurement data as deterministic feedback, and characterizing the uncertainty in UltraSurf data. OptiPro has an assortment of freeform parts in house from the optical and metal machining world. These parts will be used to test the five-axis scanning motions as well as for creating freeform error maps. The UltraSurf has already seen success in exporting the measurement data of an asphere, and correcting the resulting error on several different deterministic grinding and polishing platforms. Research will continue with using the UltraSurf as a feedback mechanism for manufacturing. The UltraSurf is neither a CMM nor an interferometer; therefore, current standards for uncertainty characterization do not directly apply. OptiPro is examining current

standards to produce a traceable qualification for UltraSurf measurement uncertainty. Simple tests such as measuring certified master parts, such as spheres and flats are the short-term solution for understanding the accuracy of the UltraSurf.

## REFERENCES

- [1] Kaya I, Rolland J, A Radial Basis Function Method for Freeform Optics Surfaces. Frontiers in Optics, OSA Technical Digest (CD), 2010
- [2] Dufour ML, Lamouche G, Detalle V, Gauthier B, Sammut P. Low-Coherence Interferometry, an Advanced Technique for Optical Metrology in Industry. Non-Destructive Testing & Condition Monitoring. 2005 Apr; 47(4):216-219.
- [3] STIL Sciences et Techniques Industrielles Technology, [Internet]. 2010 Feb [cited 2011 Jan 12]. Available from: <http://www.stilsa.com/EN/prin.htm>.
- [4] DeFisher S, Bechtold M, Mohring D, Bambrick S. An innovative non-contact surface measurement solution for asphere, deep parabolic, and ogive radome geometries. Window and Dome Technologies and Materials XI, 2009 Apr; 7302.
- [5] Zhang Z, Iterative Point Matching for Registration of Free-form Curves, 1992

# FOUR-AXIS SPHERICAL GEOMETRY MEASUREMENT OF FREEFORM SURFACES – POLARIS 3D

Alex Sohn, Kenneth Garrard and Thomas A. Dow  
Precision Engineering Center  
North Carolina State University  
Raleigh, NC, USA

## ABSTRACT

The Polaris 3D measuring machine was designed to measure precision optical and mechanical surfaces in spherical coordinates. It employs two rotary and two linear axes with a non-contacting optical probe that follows the surface of the part. It can measure a spherical part to over greater than  $180^\circ$  of included angle. This paper describes the operation of the machine and its unique ability to measure a range of mechanical and optical components. Several examples illustrating this unique measurement capability are cited. The first is combined measurement of a concave spherical surface on a cylinder. The second is an integrated pair of reflective lenses used to collimate and focus a solid state laser. The third is the cylindrical outer diameter of a fired bullet for forensic analysis.

## INTRODUCTION

The Polaris measuring machine is a patented [1] design with axes geometries that measure a part in a spherical coordinate system. This system is ideal for many optical and mechanical parts and fits well with components made on diamond turning machines. It can measure spheres and aspheres with included angles greater than  $180^\circ$ , cones, cylinders and freeform parts with departures of several millimeters from those base geometries.

## MACHINE OPERATION

### Axes Motion

The part is mounted on a horizontal spindle ( $\phi$  axis) that in turn rests on a linear axis (Z) that can move in the direction of the spindle axis as illustrated in Figure 1. A non-contacting optical probe is supported on a linear axis (R) that is mounted on a rotary table ( $\theta$ ) aligned with spindle the axis. The result is the measurement of points on the part surface in spherical coordinates. Data points, however, can be transformed into any coordinate system of interest. The optical probe is a Chromatic Aberration (CA) type with a sensing range on

the order of 300 micrometers and an angular range up to  $\pm 30^\circ$  from normal incidence, depending on the surface measured. For spherical, aspheric and freeform parts with small deviations from a sphere, the motion of the axes keeps the optical probe nearly normal to the surface. The probe signal is fed back to the controller which moves the R axis to keep the probe focused on the surface and measures radial deviations from the spherical geometry.

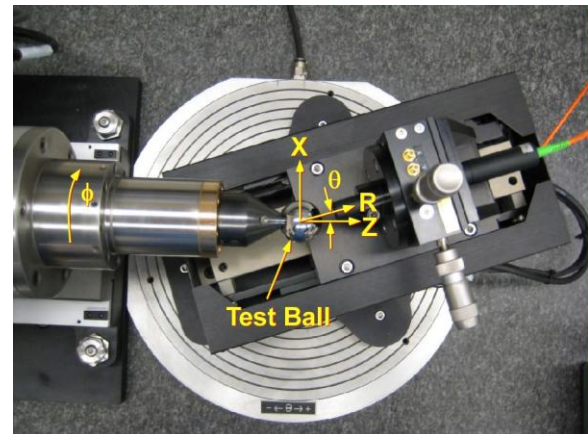


FIGURE 1. Photograph of Polaris 3D with reference ball in part holder. Axes directions are define [2].

As the angular deviation grows, both the optical probe and the Z axis provide unique measurement capabilities. Parts with large deviations from a sphere can be measured with the Z-axis stationary as long as the deviations are within, the acceptance angle of the probe. If, however, the angular range of the probe is exceeded, the Z-axis can be moved to vastly extend the measurement capability of Polaris 3D.

Figure 2 illustrates the effect of moving the center of the part in the Z direction away from the center of the rotation. In the top image and Equation (1), the probe is normal to the sphere and the coordinates for Z and X are sine and cosine components of  $R_1$ . For the lower image

and Equation (2), the Zoffset is added to the components of  $R_2$  and the probe angle is different, but the surface coordinates are the same. The movement of Z can also be done during the measurement to hold the probe within its angular range.

$$x_1 = R_1 \cos \theta_1 = R_2 \cos \theta_2 = x_2 \quad (1)$$

$$z_1 = R_1 \sin \theta_1 = R_2 \sin \theta_2 + z_{\text{offset}} = z_2 + z_{\text{offset}} \quad (2)$$

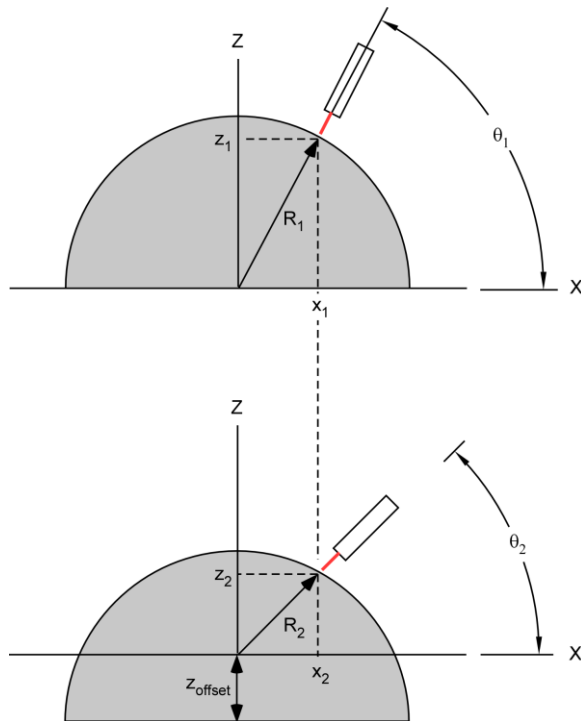


FIGURE 2. Measurement of a sphere centered with the probe rotary table (top) and with a Zoffset (bottom).

Another example of the utility of the Z axis is the measurement of a concave spherical surface and its fiducial OD. This situation often arises for injection mold inserts where the OD of the insert is used for axial alignment of the two surfaces of a lens. As shown in Figure 3, both the concave surface and the cylindrical OD can be measured by moving the part in the Z-direction. Since the part is never removed from the machine, alignment is maintained and the relationship between the surfaces can be determined.

#### Alignment and Error Correction

The unique combination of axes on the Polaris 3D provides a direct measurement of the radii of a part. However, this measurement requires careful alignment of the axes and compensation

of the errors on each axis. The motion of each axis was characterized and the coupling geometry to measurement error was determined. Adjustment of the mechanical alignment was included in the design of the machine and compensation for errors beyond the mechanical alignment has been implemented.

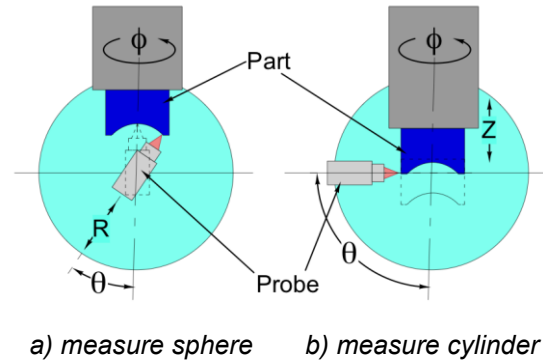


FIGURE 3. Example of the measurement of a concave sphere on a cylinder. (a) The sphere is measured with its center of curvature approximately coinciding with the machine origin and the  $\theta$ -axis sweeping through an angle (b). The  $\theta$ -axis is then positioned at  $90^\circ$  and the Z-axis is moved during measurement to gather data on the cylindrical face (b).

One important error was the Z-axis straightness in the X-direction. This affects the alignment of the two rotary axes ( $\theta/\phi$ ) as a function of Z-axis position, a critical parameter since this alignment is the basis for the spherical coordinate system. The straightness measurement in Figure 4 shows a peak-to-valley error of  $1.2 \mu\text{m}$  with the error zeroed at  $Z = -50.2 \text{ mm}$ . Independent measure of the  $\theta/\phi$  alignment at  $Z = -50.2 \text{ mm}$  produces a reference point with a constant error where contribution from Z-axis straightness is zero. Errors due to straightness of the Z-axis are added to the  $\theta/\phi$ -alignment error for correction.

#### Setup and Data Collection

For surfaces roughly spherical or aspheric, data is collected with the part spindle rotating and the polar ( $\theta$ ) axis sweeping through a range of angles to create a spiral pattern of points on the surface. The density of data can be specified by the operator, but typically 25,000 data points are collected in 30 seconds with the part spinning at 100 rpm. The combination of the R axis and CA probe reading is the radius at each  $(\theta, \phi)$  point. The data from each of the axes are then



combined to produce a complete surface map. For cylindrical and conical parts, the Z axis is moved during measurement while the  $\theta$  axis remains stationary and the part is rotated about the  $\phi$  axis. More complex geometries can be measured with a combination of Z and  $\theta$ -axis motions.

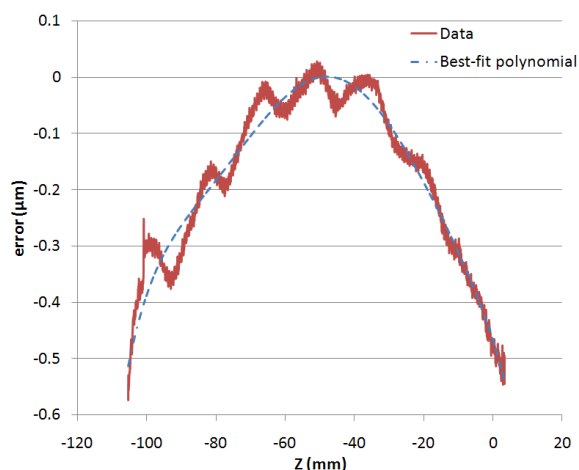


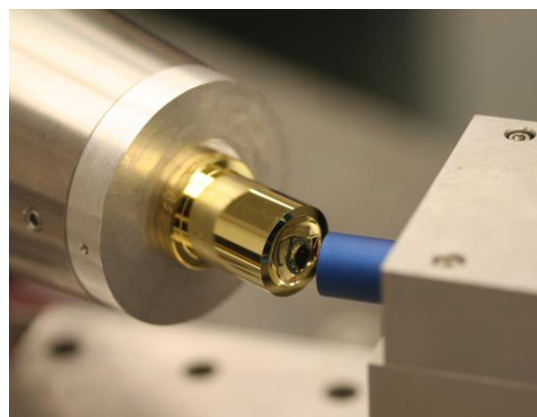
FIGURE 4. Z-axis horizontal straightness as measured with a capacitance gauge against a Zerodur straightedge.

### Measurement and Data Analysis

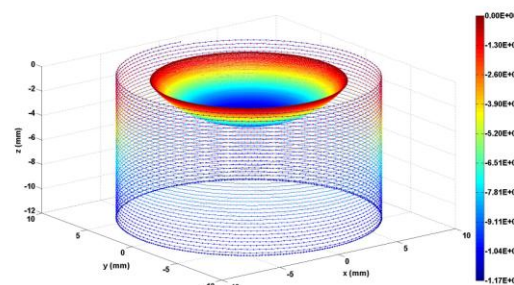
Once the data is collected, error compensation is applied and the resultant shape is compared with the design intent or the best fit conic surface to the data. Three complex examples are presented; 1) a concave sphere related to a reference cylinder, 2) a monolithic combination of two lenses for focusing the output from a laser diode, and 3) rifling marks on a bullet for forensic analysis.

### SPHERICAL LENS MOLD MEASUREMENT

The measured spherical lens mold is a concave spherical surface on a cylinder. Concentricity of the diamond-turned lens surface and cylindrical periphery of the mold are critical. The unique capabilities of Polaris 3D make this measurement straightforward. The result in Figure 5(a) shows the sphere being measured which would be followed by the cylinder measurement. Figure 5(b) is the data generated from both measurements shown on the same coordinate system. Since they were measured in the same setup, the surfaces can be individually analyzed but still related to each other in an absolute way.



a) Photograph of the measurement



b) Data of the concave sphere and cylinder  
FIGURE 5. Measurement of diamond-turned concave sphere in a cylinder.

### MONOLITHIC REFLECTIVE LENS SET

The second example is a two-mirror optical system consisting of an asphere and a biconic corrector used for focusing the output of a laser diode illustrated in Figure 6. This system corrects the characteristic anamorphic beam profile of the diode as well as focuses the beam at a distance of 100 mm.

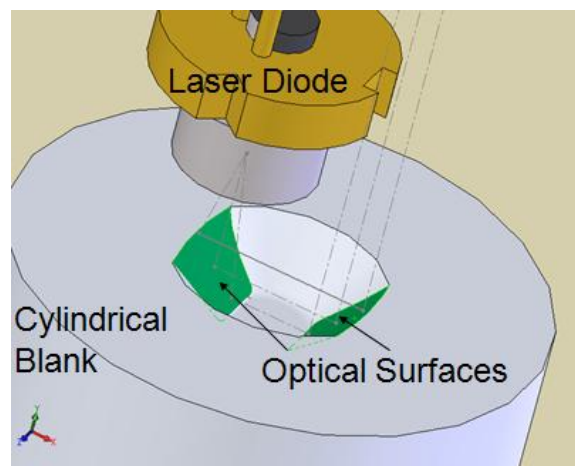


FIGURE 6. Schematic showing the two-mirror optical system measured using Polaris 3D in four-axis mode. The center separation is 4 mm.

The machined part is shown in Figure 7, with the two mirrors appearing as nearly flat in the image. The surfaces were machined in SAE 360 brass using the PEC's Flora II fast tool servo [3].

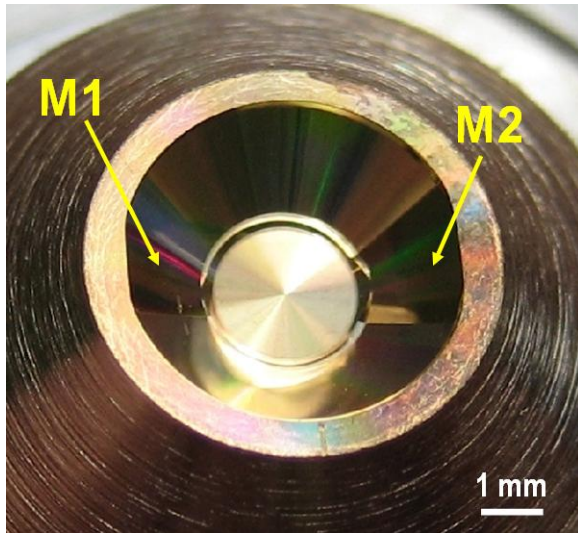
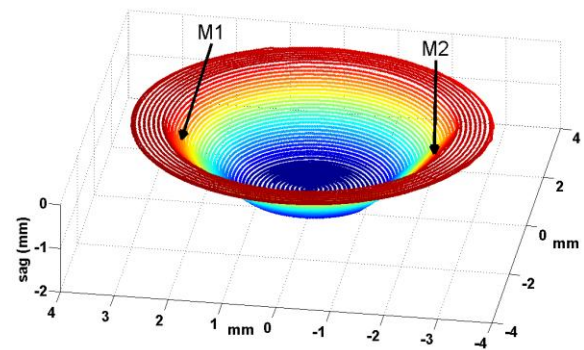


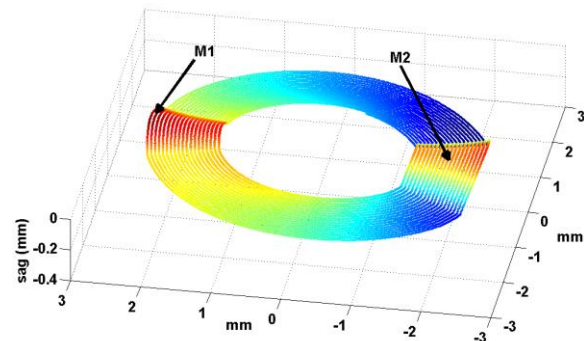
FIGURE 7. Image of the machined optical system

The concave surface shown in Figure 7 was measured on Polaris3D by parking the rotary table ( $\theta$ ) at  $+30^\circ$ , spinning the part at 20 rpms and translating the Z axis (and the part) away from probe. With tracking engaged, the controller moves the R axis to keep the probe focused on the part. This setup allowed the probe to see the flat at the bottom of the part, the conical mirror surfaces and a portion of the upper rough machined flat. The diamond turned center flat is useful for alignment of the optic and to remove tilt before comparing the measurement data with the intended surface shape.

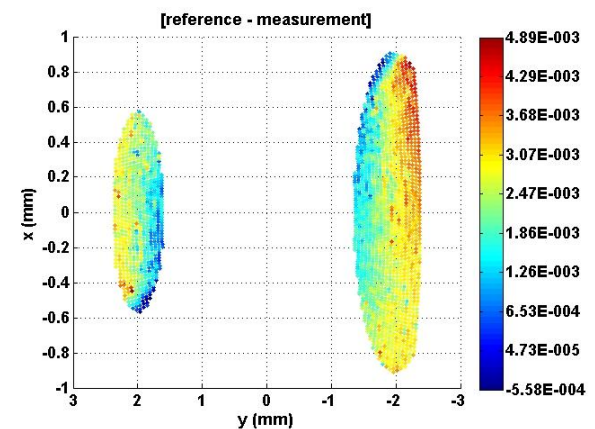
Figure 8 shows the measurement results. Figure 8(a) is a plot of the raw measurement data for the optical system. This base cone was subtracted in Figure 8(b) indicating the tool motion away from the cone (toward the center of the part) needed to create the nearly flat mirror surfaces. Figure 8(c) is a top down view of the error when the measurement is subtracted from the shape of the optical design (reference). The result is an RMS error of 730 nm with the error largest on the outside and smallest on the inside. The result is a tilt angle that is 5 milliradians more than desired.



a) Optical system measurement



b) Measurement after removal of cone



c) Reference surface minus measurement for reflective optic

Figure 8. Measurement with Polaris3D of the machined optical system. The RMS error is 730 nm and the PV is  $5.4 \mu\text{m}$  after alignment of the reference and measurement data sets.

## BULLET MEASUREMENT FOR FORENSIC ANALYSIS

The third example involves the measurement of a fired bullet as shown in Figure 9(a). By measuring the periphery of the bullet, marks uniquely created by the rifling of a particular weapon can be identified. The measurement

capability of Polaris 3D provides a profile of the entire periphery of a fired bullet as shown in Figure 9(b) to sub-micrometer accuracy. The measurement was acquired with the  $\theta$ -axis fixed at  $90^\circ$ , translating only Z while the R-axis follows the surface using feedback from the optical probe. A 10 mm diameter cylinder was subtracted from the data and plotted on an arbitrary radius to show the deviations. The large-scale features on the bullet (as shown on the color bars in Figure 9(b)) are on the order of a 200  $\mu\text{m}$  and their location and height compared to another bullet fired from the same gun should be the same. Another way to present the results is to unwrap the cylinder in Figure 9(b) and present the data as a plane in Figure 9(c). Unwrapping the cylinder produces a clearer profile of the marks. This profile can be compared to other samples and, eventually matched to a particular weapon.

## CONCLUSIONS

Measurement of complex optical and mechanical components found a standard in the Polaris 3D. The spherical coordinate system is ideal for most optical systems and the capability to move the part during the measurement greatly expands the range of part shapes. Three examples were described ranging from a concave spherical lens mold, an integrated two-mirror optical system for laser diode and a fired bullet.

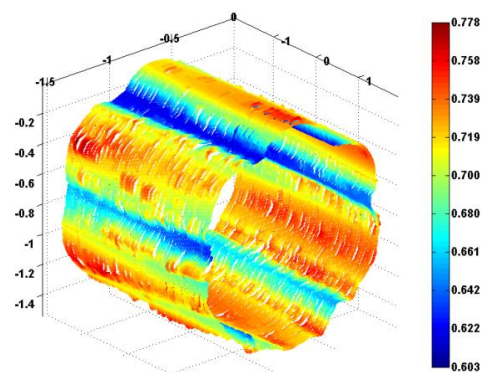
Once the data on the positions of each of the 4 Polaris axes has been collected, the results must be presented in a form that meets the needs of the user. For the examples presented here, the results are compared to the desired or design shape. However, for some measurements such as the fired bullet, manipulation of several data sets must be performed to find similarities. The increased metrology capability of Polaris 3D carries with it new challenges in data analysis and representation. The extent of these challenges is increasingly dependent on the vision of the end user and interaction between that user and the metrologist is the key to success.

## REFERENCES

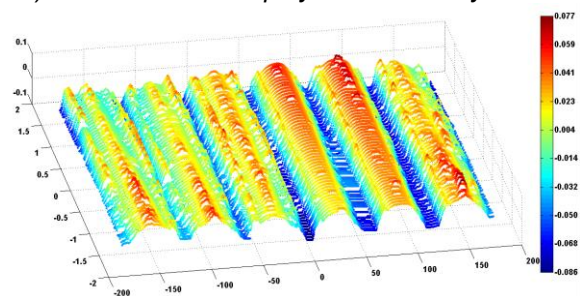
- [1] A. Sohn, Kenneth P. Garrard and Thomas A. Dow. Polar Coordinate-Based Profilometer and Methods. United States Patent No. 6895682. November 2002.



a) Photograph of bullet



b) Bullet features displayed on arbitrary radius



c) Bullet features unwrapped

FIGURE 9. Image of the OD of a fired bullet showing features from rifling

- [2] Sohn, K. Garrard and T. Dow, The spherical profilometer *Polaris3D*. Proceedings of the Twenty-fourth Annual Meeting of the ASPE, 47, 43-46 (2009).
- [3] Garrard, K, Sohn, A. and T. Dow, Freeform Surface Fabrication in Cylindrical Coordinates, Proceedings of the ASPE Spring Topical Meeting, 2011.



# SLOPE MEASURING METROLOGY FOR PRECISION FREE-FORM SURFACES

R. E. Parks, P. Su, T. Zobrist<sup>1</sup>, T. Su, W. H. Park, M. Dominguez,  
L. Wang, G. Zhu, G. Butel, S.-H. Lu, Y. Wang, P. Zhou, and J. H. Burge

College of Optical Sciences

<sup>1</sup>Steward Observatory Mirror Lab

University of Arizona

Tucson, AZ 85721

## INTRODUCTION

The beginnings of quantitative slope measurement of specular surfaces, called reflection deflectometry in some fields, dates from the Foucault knife edge test of concave mirrors reported in 1858. Over time this basic one dimensional test has been improved as the wire test and the Ronchi test. It was extended to two dimensions by Hartmann (1900) and used to guide the polishing of the 5 m Hale telescope hyperboloidal primary mirror finished in 1947. Work to use the method for the study of plate bending began by Ligtenberg [1] in 1954 in Germany. The work on reflection deflectometry continues to this day [2].

## Initial Work at Arizona

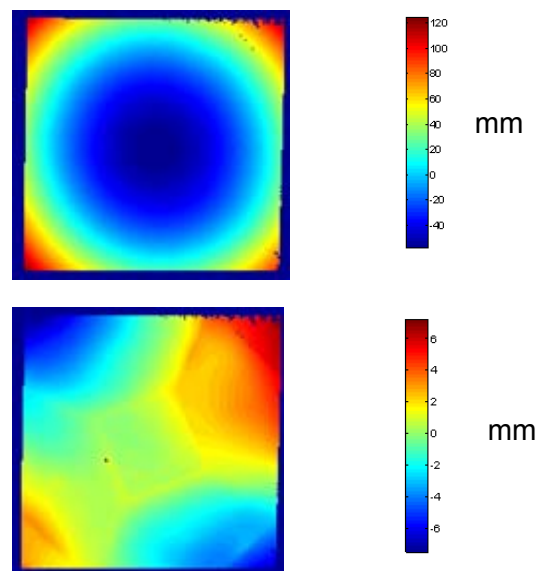
With his background in astronomy and current interest in solar concentrators, Roger Angel realized that detailed slope measurements of crudely formed solar concentrating optics could be made with no more hardware than a laptop computer. [3]. He envisioned the monitor acting effectively as a single point source that could be rastered in 2 dimensions across the screen and the built-in camera to sense reflection from each point on the reflector. With the screen positioned at the center of curvature of the concentrator, a pixel, or small group of adjacent pixels, would be illuminated and the camera would record the location on the concentrator of the reflection of the pixel(s). The illuminated pixel would be moved, a new picture taken with this continuing until the whole surface had been sampled.

## MEASUREMENT OF HIGHLY ABERRATED SURFACES

In practice there are several disadvantages to this particular scheme and one of us (P. Su) proposed using rows of pixels on a separate monitor at the center of curvature to gather the slope data. This scheme was used to measure a

single, off axis, molded segment of a solar concentrator about 800 mm in size. The resulting contour map had high spatial and angular resolution, and immediately got us thinking about using the method on precision optics. The next step forward was using the test, now dubbed SCOTS for Software Configurable Optical Test System, to measure a large molded surface. It was clear that the method was useful for both aligning segments relative to each other as well as determining the performance of individual segments.

Current work involves tests of a crudely molded, monolithic reflector 1.6 m on a side. Fig.1 shows a surface map made by integrating the slopes (a) and the shape error (b) after subtracting the ideal shape.



**FIGURE 1.** Sag of 1.6 m square solar collector (upper), departure from specified shape (lower)  
This example gives a feel for the potential dynamic range of height measurement while still having good spatial resolution.

If the raw slope data is viewed after removing the lowest order spatial variations it reveals the high spatial frequency slope errors resulting from the initial misalignment of the mold segments as seen in Fig. 2a. Further, the slope measurements can be easily turned into estimates of the concentrator efficiency to focus light into a small area as in Fig. 2b.

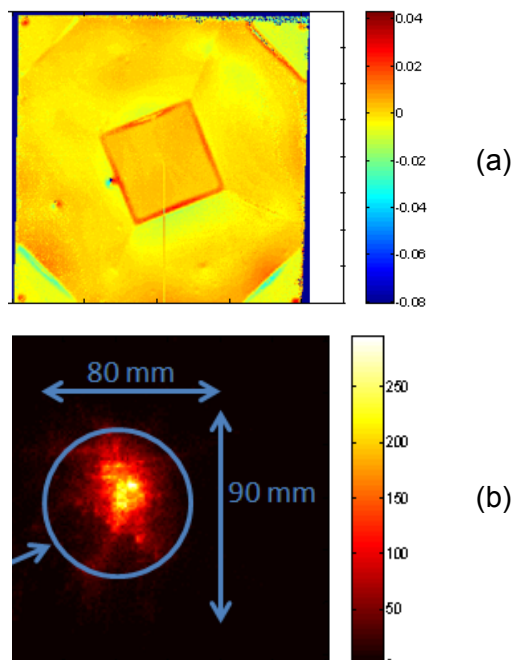


FIGURE 2. Residual high spatial frequency radial slope error in radians (a), energy concentration (AU) based on the radial slope above with astigmatism removed (b). Circle shows 80% concentrator efficiency.

#### APPLICATION TO PRECISION OPTICS

The success with initial measurements of solar panels led us to try the SCOTS method to testing a severely aspheric precision optic, one of the 8.4 m segments for the Giant Magellan Telescope (GMT). This off-axis parabola departs from a sphere by 14 mm peak-to-valley. A large part of this departure is corrected in the null test by a 3.8 m tilted sphere, but the residual slope errors are enough to make the minimum spot diameter at the focus of the test about 150 mm in diameter. As is the case for most aspheric mirrors the most difficult part of the polishing effort is at the edge and the mirror had sufficient slope errors that the interferometric test could not produce valid data.

Once the hardware was aligned so that the full aperture of the GMT mirror was visible in the

camera the SCOTS data was valid and useful all the way to the edge of the mirror. The polishing has been guided by both SCOTS and interferometry since that time. The most recent results, given in Fig. 3, show the same contour where there is valid data for both tests and SCOTS data to the very edge.

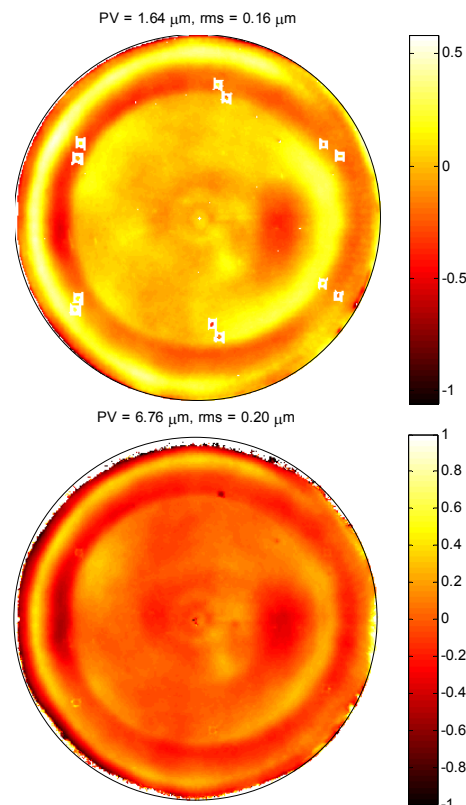


FIGURE 3. Surface of GMT mirror based on slope measurement (upper) and interferometric null test (lower). High regions and missing data at edge bias the interferometric PV and rms.

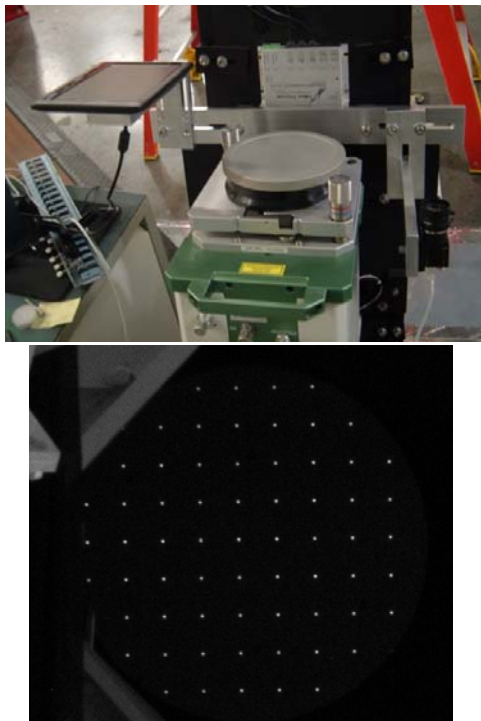
#### Concerns with Low Order Alignment Terms

Initially the SCOTS test results were somewhat degraded by inconsistencies in determining the low order aberrations, or low spatial frequency errors. This is in part due to the very small change in slope from ideal for the low spatial frequency errors and thus lack of sensitivity to this kind of error. Another part is due to distortion in the camera lens that causes a mapping error between the location of the reflection on the surface and where it is recorded on the array detector. This means that when fitting the errors the spatial coordinates of the fit are not quite correct so the aberration coefficients are slightly in error.



By careful alignment and calibration of the camera lenses it is possible to reduce the noise in the calculation of low spatial frequency errors to the 10 nm rms level for large (4 m diameter) optics. This amounts to detecting an error of 4 seconds of arc across the 4 m optic. Further experiments are underway to determine the limits of uncertainty as a function of spatial frequency in slope measurement.

One controlled experiment makes use of the permanently installed interferometer at the center of curvature of the large (4 m) fold sphere used as part of the GMT null test. Mounted on either side of the interferometer are a screen and camera as shown in Fig. 4.

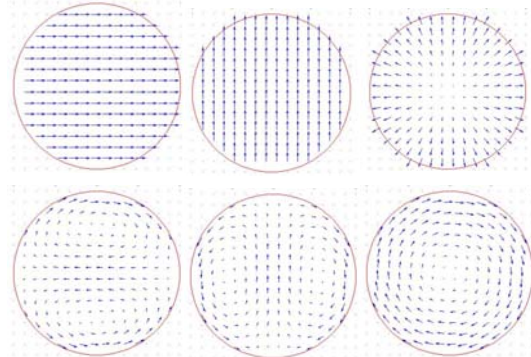


*Figure 4. Screen to left, and camera to right of interferometer, transmission sphere covered (upper), view of spot array reflected from fold sphere (lower).*

Using this arrangement it is possible to simultaneously measure the sphere with both the interferometer and the SCOTS setup. The simultaneity is necessary since air turbulence affects the wavefront on a short term temporal scale and thermal effects affect the result on a somewhat longer time scale. These experiments are currently on going, but are what lead to the conclusion that the low order SCOTS aberration terms match the interferometric ones at the 10 nm rms, or so, level.

### **Polynomials for Analyzing Alignment**

In terms of alignment, some useful vector polynomials based on Zernike polynomials have been published that describe slope data over a circular aperture [4,5]. A set of six low order ones describe the aberrations expected due to misalignment of screen to mirror. These six, corresponding to six degrees of rigid body misalignment are shown in Fig. 5. The first three represent translations while the final three rotations of the screen.



*Figure 5. Six orthogonal vector polynomials representing slope errors due to misalignment by translation (upper) and rotation (lower).*

### **TEST OF ROUGH AND CONVEX SURFACES**

Up until now we have discussed testing specular concave optics, the easiest configuration to test and least exciting among free-form surfaces. For slope measuring tests to be of real interest and use, they must address non-specular, or rough, and convex surfaces. First, it must be pointed out that reflection deflectometry is much more sensitive than fringe projection deflectometry that is somewhat better known [6]. In fringe projection, a sinusoidally varying pattern of light stripes is projected on a surface that will bend the fringes proportionally to the local slope of the surface. The light scattered from the surface is recorded by a camera. The signal to noise level of the pattern reaching the detector is a function of the contrast of the scattered light from the surface and the distance to the camera since the camera aperture subtends a small amount of the total scattered light.

In reflection deflectometry, only specularly reflected light from the surface that enters the camera aperture reaches the detector. If the screen has high contrast and the ambient light is relatively low, a very high contrast signal reaches the detector. Further, the camera aperture defines the angular sensitivity of the test where the projection technique does not

measure angle at all but derives it from the fringe bending. Based on data analysis the reflection method has an angular sensitivity of about 1 part in 10,000 of the field of view of the camera lens.

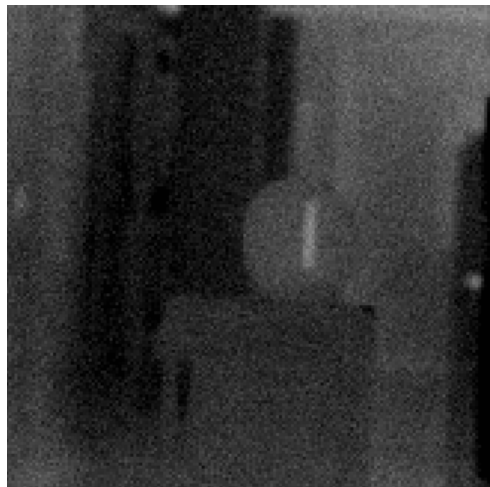
### **Infrared slope measurement tests**

Given the superiority of the reflection method, how can it be used with non-specular surfaces? The answer is to move the wavelength of the light used in the test to the infrared. At a wavelength of 10  $\mu\text{m}$  surfaces 20 times rougher than those deemed specular in the visible can be tested in reflection. For our use in optics manufacturing it means we can test ground glass surfaces during the generation of the asphere in the surface, a process at least an order of magnitude faster than polishing in changing the shape of a surface. For machined parts it promises the ability to do optical, non-contact testing of surfaces that would not previously have been possible.

To do the IR SCOTS, a heated wire replaces the monitor screen and a microbolometer camera the CCD. The wire is slowly translated perpendicular to the optical axis of the mirror in a plane near the center of curvature while the camera records the reflection of the wire in the ground surface. An example of this is shown in Fig. 6. On top is a view from behind the mirror looking at the hot wire stage and IR camera on the orange cart. The wire is vertical and about 250 mm long. Below is the picture from the IR camera that demonstrates the feasibility of the method. The light vertical stripe on the round mirror in the lower center is the reflection of the wire. In a real test the camera field of view must be better matched to the surface being tested.

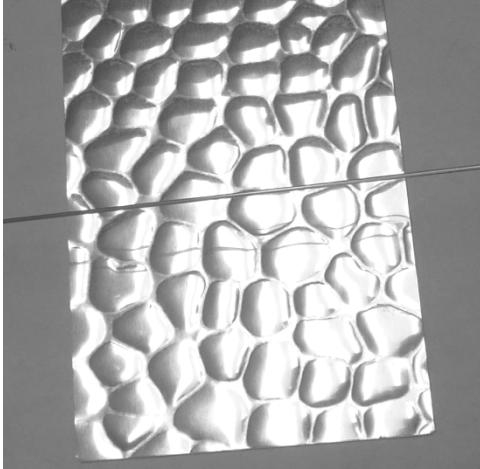
### **SCOTS for Other Geometries**

For other geometries, there are other issues. For flat surfaces, the screen must be at least twice as large as the flat being tested. Although we have yet had time to look at this test it might work well as a test for unchucked silicon wafer flatness where the flatness is generally too great to test in an interferometer. For convex surfaces, techniques such as that used by Campos-Garcia [7] with, effectively, multiple screens or a single screen and a rotary table to stitch data together can be used. An issue with convex surfaces is knowing exactly where the reflection occurs on the surface. An error there leads directly to an error in surface height.



*Figure 6. IR SCOTS setup looking at back of mirror (upper) and reflection of hot wire in mirror seen by IR camera (lower).*

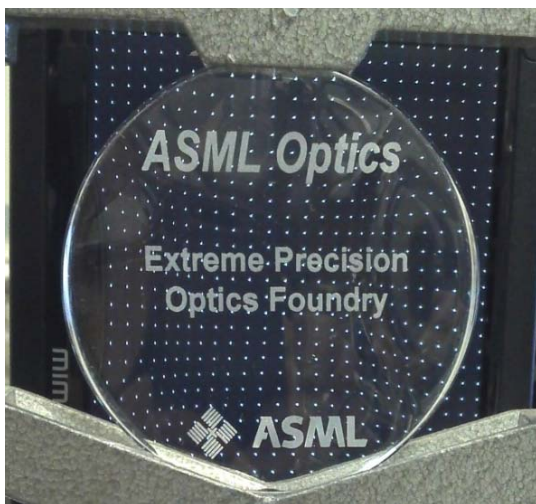
Another possibility that we have yet to investigate is moving a straight object across a convex surface near to the surface. This is illustrated in the crude example in Fig. 7 where a piece of piano wire is held above an embossed aluminum surface. The camera records the wire and its image in the surface. Clearly the wire is the high contrast straight line while the image is the wavy, lower contrast line below it. Clearly better lighting, focus and background would improve the quality of the data. On the other hand, it does illustrate that wildly free-form surfaces are amenable to reflective slope measurement.



*Figure 7. Straight line object above an embossed surface and its reflected image.*

### TESTS OF REFRACTING OPTICS

As a last example of deflectometry or SCOTS, the test can be done in transmission by placing the screen on one side of the lens and camera on the other [8]. As in the case of mirrors, the camera is focused on the lens, or surface, and the transmitted spots or stripes are out of focus and their diameter depends on the camera aperture setting. Fig. 8 shows a series of bright spots on a dark screen distorted by a souvenir sample asphere by ASML. Again, all this suggests is feasibility but initial results from this type of test look promising. One aspect of this type test that interferometry cannot do is use multiple wavelengths, something that is easy to program into the video screen.



*Figure 8. Even array of spots on monitor screen distorted by an aspheric lens.*

Of course, another aspect of testing refractive single elements is that they will all have significant spherical aberration if tested alone. Yet this does not matter for slope tests because, as long as the lens is modeled correctly, slope tests are inherently non-null. Designing a “null-pattern” of stripes or dots is as easy as running a model in a lens design program. The test consists of comparing the model stripe or dot pattern with the measured one and finding the errors from the difference.

### SLOPE AS A SPECIFICATION OF OPTICS

Lastly is the subject of how optical free form surfaces are specified. For historical reasons because spheres are easy to make and test, and because the laser was invented before computing power became ubiquitous, optical surfaces are specified in terms of height departure from a spherical surface. Except in the highest quality optical systems the real contributors to good imaging performance are slope errors. This becomes more of a concern as more systems incorporate aspheres, and that these aspheres are often made using deterministic processes that tend to introduce high spatial frequency errors in the surface, that is, slope errors.

One could argue that this same idea does not apply to other types of manufactured surfaces. However, take for example plastic molded parts. There is an aesthetic requirement that the surfaces have a certain smoothness that is usually in the subjective eye of an inspector. We believe that beginning to fashion a general two dimensional slope specification for specular surfaces would be in the interest of industry. We have already shown there are many slope measuring tests for specular surfaces that could be used to quantitatively measure surfaces produced to the specification.

### CONCLUSIONS

A variety of optical tests using slope measuring techniques have been illustrated to show the potential breadth and precision of the method, and its potential application to the non-contact measurement of free form surfaces whether they be optics or other manufactured surfaces. While the basic method is over 100 years old, and many people have improved on the method over the years, modern consumer based electronics

promises to make the method widely adopted for many inspection tasks because the hardware is inexpensive and the method is easy to understand and implement.

## ACKNOWLEDGEMENT

The authors are grateful for support from NIST, U.S. Dept. of Commerce, under ARRA Award #60NANB10D010. Initial funding was provided by a State of Arizona TRIF Award.

## REFERENCES

- [1] Ligtenberg as cited by Ritter R, Hahn R. Contribution to Analysis of the Reflection Grating Method. *Optics and Lasers in Engineering*. 1983; 4: 13-24.
- [2] Tang Y, Su X, Wu F, Liu Y. A novel phase measuring deflectometry for aspheric mirror test. *Opt. Express*. 2009; 17, 19778-19784.
- [3] Parks R. SCOTS: A Fast, Inexpensive Test of Solar Concentrators. *Optics for Solar Energy*, OSA Technical Digest. 2010; paper STuA2.  
Also see [www.rioglassolar.com/v\\_portal/apartados/apartado.asp?te=3](http://www.rioglassolar.com/v_portal/apartados/apartado.asp?te=3)
- [4] Zhao C, Burge J. Orthonormal vector polynomials in a unit circle, Part I: basis set derived from gradients of Zernike polynomials. *Opt. Express*. 2007; 15, 18014-24.
- [5] Zhao C, Burge J. Orthonormal vector polynomials in a unit circle, Part II: completing the basis set. *Opt. Express*. 2008; 16, 6586-91.
- [6] Creath K, Schmidt JJ, Wyant J. Optical Metrology of Diffuse Surfaces. In *Optical Shop Testing*, Malacara D. ed. 3<sup>rd</sup> ed. Wiley 2007.
- [7] Campos-García M, Díaz-Uribe R, Granados-Agustín F. Testing Fast Aspheric Convex Surfaces with a Linear Array of Sources. *Appl. Opt.* 2004; 43, 6255-64.
- [8] Knauer M, Richter C, Vogt P, Häusler G. Measuring the refractive power with deflectometry in transmission. *DGaO-Proceedings*. 2008; 109, A24.



# ADAPTIVE INSPECTION OF FREE-FORM SURFACES IN COORDINATE METROLOGY

Rocco Ascione<sup>1</sup>, Giovanni Moroni<sup>2</sup>, Stefano Petrò<sup>2</sup>, and Daniele Romano<sup>3</sup>

<sup>1</sup>Dipartimento di Ingegneria Industriale  
Università degli Studi di Cassino

Via G. di Biasio 43, 03043 Cassino, Italy

<sup>2</sup>Department of Mechanical Engineering  
Politecnico di Milano

Via La Masa 1, 20156, Milan, Italy

<sup>3</sup>Department of Mechanical Engineering  
University of Cagliari

Piazza d'Armi 1, 09123 Cagliari, Italy

Coordinate metrology is the most widespread technology for assessing compliance of mechanical parts to dimensional and geometric specifications. Coordinate Measuring Machines (CMM), devoted to such task, inspect the part by acquiring the coordinates of a discrete set of points on the relevant surface by touching each point under a computer controlled measurement cycle. Point cloud is then fitted by a suitable substitute geometry, from which local and global geometric deviations are evaluated. Although CMM are slower than optical devices, like videocameras and laser scanners, they are still unsurpassed in the accuracy of point measurement and level of process automation.

However, CMM inspection is undermined by a well known problem in the coordinate metrology community, referred to as methods divergence. Firstly described in 1988 [1] it can be stated as follows. On one hand, the machine probes the part surface point-wise and economic constraints force the set of measured points to be small. On the other hand, form errors, as defined by tolerancing standards [2], depend heavily on extreme values [3] of the form deviations over the related. For example, straightness is defined as the minimum distance between two parallel lines enclosing the actual feature (Minimum Zone criterion). Hence a few points, the most “outward” and “inward” points, have the highest leverage on the straightness error whereas all the others have none, see Figure 1.

Although this situation lends itself to a statistical approach [4], common practice is to inspect the part over a predetermined small point sample and to compute the error by applying a deterministic

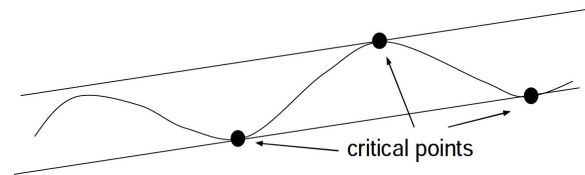


FIGURE 1. Straightness error of the profile is determined by only three critical points.

algorithm. Typical fixed-size plans adopt simple sampling strategies: uniform, pure random, Latin Hypercube, stratified. A few variable-size adaptive plans, where the next point is selected based on the previously collected information, can also be found in the literature [5, 6, 7]. These methods based are on some fitting technique, e.g. splines [5] or not, e.g. tabu search [6] and Gaussian curvature [7]. However these adaptive methods are deterministic in nature. Opposed to this, we propose statistical adaptive plans where predictions from Kriging models, sequentially estimated at each step of the procedure, are used to select the next point to inspect. The idea is that the critical points in Figure 1 can be finally caught by a sequence of prediction models of the surface pattern with increasing accuracy. The inspection plans introduced here are an upgrade of those already presented in [8]. In the next section the general concepts of Gaussian Process and Kriging are introduced; then the method is described in the subsequent section and, in the last section, is applied to a case study concerning the estimation of the profile error of a free-form surface. The method and the case study were introduced in a previous work [9], in the case in which the profile tolerance is completely constrained by a datum reference system. In this work the methodology is extended to the datum-free case.



## ADAPTIVE PLANS DRIVEN BY GAUSSIAN PROCESS (GP) MODELS

The choice of Kriging models to drive the adaptive search of informative sampling locations is dictated by their recognized predictive capability [10].

Let  $D \in \mathbb{R}^d$  be the region where we want to predict the profile ( $d = 1$ ) or the surface ( $d = 2$ )  $y$ . The latter is sequentially observed in the incremental  $n$ -point designs  $\mathbf{x}_n = (x_1, x_2, \dots, x_{n_0}, \dots, x_n) = (\mathbf{x}_{n-1}, x_n)$ ,  $x \in D$ ,  $n = n_0, n_0 + 1, n_0 + k, n_0 + K$ , providing the incremental response samples  $\mathbf{y}_n = (y_1, y_2, \dots, y_{n_0}, \dots, y_n) = (\mathbf{y}_{n-1}, y_n)$ . Here  $n_0$  is the size of the initial design (at step  $k = 0$ ), while at the last step  $K$  the design size is  $n_0 + K$ . Response  $y(x)$  is considered a realization of the GP  $Y(x)$ :

$$Y(x) = \mu + Z(x) \quad (1)$$

where  $\mu$  is a constant and  $Z(x)$  is a GP with zero mean and stationary covariance over  $D$  so that:

$$\begin{aligned} E(Y(x)) &= \mu \\ \text{Cov}(Y(x), Y(x+h)) &= \sigma_Z^2 R(h; \theta) \end{aligned} \quad (2)$$

where  $\sigma_Z^2$  is the GP variance, and  $R$  is a stationary correlation function (SCF) depending only on the displacement vector  $h$  between any pair of points in  $D$  and on a parameters set  $\theta$ . The model defined by (1) and (2) is known as simple Kriging. A flexible choice for the GP correlation function is the power exponential function:

$$\begin{aligned} R(h; \theta) &= \prod_{i=1}^d \exp \{ -\theta_i^{-1} |h_i|^{p_i} \} = \\ &= \exp \left\{ -\sum_{i=1}^d \theta_i^{-1} |h_i|^{p_i} \right\} \end{aligned} \quad (3)$$

$$0 < \theta_i < \infty, \quad 0 < p_i \leq 2, \quad d = 1, 2$$

where  $\theta = (\theta_1, \dots, \theta_d, p_1, \dots, p_d)$  is a vector of unknown scale parameters  $(\theta_1, \dots, \theta_d)$  and smoothing parameters  $(p_1, \dots, p_d)$  respectively. Parameter  $\theta_i$  describes how rapidly correlation decays in direction  $i$  with increasing distance  $|h_i|$ . Parameter  $p_i$  describes the shape of the correlation decay. When  $p = 2$  we have the (improperly) called Gaussian SCF which is suitable for very smooth responses. In general, the less smooth the response the lower is  $p$ .

At the generic step  $k$  of the procedure, where the design has run size  $n = n_0 + k$ , the parameter

vector  $\theta$  is estimated by Maximum Likelihood:

$$\hat{\theta}_{nML} = \underset{\theta}{\operatorname{argmin}} [n \log \hat{\sigma}_{Zn}^2(\theta) + \log(\det \mathbf{R}(\theta))] \quad (4)$$

where  $\mathbf{R}$  is the  $n \times n$  correlation matrix whose  $(i, j)$  element is the correlation  $R(h_{ij}; \theta)$  between design points  $x_i$  and  $x_j$  and the process variance is also estimated by ML:

$$\hat{\sigma}_{Zn}^2(\theta) = (\mathbf{y}_n - \hat{\mu}_n)' \mathbf{R}(\theta)^{-1} (\mathbf{y}_n - \hat{\mu}_n) \quad (5)$$

with  $\hat{\mu}_n = \frac{1}{n} \sum_{i=1}^n y_i$ . Finally predictions, based on a  $n$ -point design, are obtained by

$$\hat{Y}_n(x) = \hat{\mu}_n + \mathbf{r}_x' \mathbf{R}^{-1} (\mathbf{y}_n - \hat{\mu}_n) \quad (6)$$

where  $\mathbf{r}_x$  is the correlation vector  $(R(x - x_1), \dots, R(x - x_n))'$ . The predictor obtained by plugging in (6) the estimates  $\hat{\mathbf{r}}_x = \hat{\mathbf{r}}_x(\hat{\theta})$  and  $\hat{\mathbf{R}} = \hat{\mathbf{R}}(\hat{\theta})$  is called the *Empirical Best Linear Unbiased Predictor* (EBLUP). However, predictions are no longer linear in the observations as  $\hat{\mathbf{r}}_x$  and  $\hat{\mathbf{R}}$  may have a highly non-linear dependence on observations. Another notable consequence of using the EBLUP is that mean square prediction error (MSPE) of the GP, also known as *Kriging variance*, i.e.

$$\begin{aligned} MSPE[\hat{Y}_x] &= E((\hat{Y}_x - Y(x))^2) = \\ &= \sigma_z^2 (1 - \mathbf{r}_x' \mathbf{R}^{-1} \mathbf{r}_x) \end{aligned} \quad (7)$$

underestimates prediction variance as it does not account for the extra variability transmitted to  $\hat{\mathbf{r}}_x$  and  $\hat{\mathbf{R}}$  by  $\hat{\theta}_{nML}$ . Therefore we will use an empirical estimate of prediction variance based on Jackknifing and Cross-Validation [10]. The method is explained in the Appendix.

## THE ADAPTIVE PROCEDURE

A schematic view of the adaptive construction of the inspection plans is shown in Figure 2. At the first step of the procedure ( $k = 0$ ) a set of  $M$  candidates sites,  $\mathbf{c}_0 = (c_{10}, c_{20}, \dots, c_{M0})$ , from which probing locations are selected, is defined. Note that the size of the candidate set  $\mathbf{c}_k$ , at step  $k$ , is  $M - k - n_0$  since one candidate site is taken out at each step. Because the without datum profile geometric error is being evaluated, sampling points are now aligned to the nominal geometry according to some criterion (usually least squares or minimum zone). This allows the evaluation of the local geometric error for every point, and also

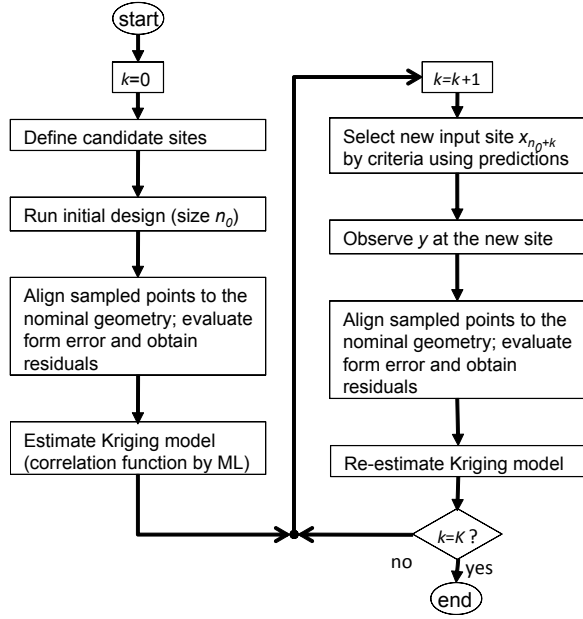


FIGURE 2. Scheme of the adaptive procedure for form error estimation.

of the overall geometric error. Then the initial design with fixed-size  $n_0$  is run on the local errors to enable the first estimation of the correlation function of the Kriging model and the subsequent estimation of the form error based on predictions by the model,  $\hat{t}_{n_0}$ . Next-point selection is the core of the procedure.

The selection rule combines two criteria. One is problem-specific and the other is informative. The problem-specific criterion (*MaxtInc*) chooses as next point the candidate which, if added to the current design, gives the maximum expected increase of form error:

$$x_{n_0+k} = c_{j^*k}, \quad j^* = \operatorname{argmax}_{1 \leq j \leq M-k} \hat{y}_{jk} \quad (8)$$

where  $\hat{y}_{jk}$  is the Kriging forecast (according to (6)) of the local geometric deviation at position  $j$  and step  $k$ . It can be supposed that the addition of this points causes the maximum variation of the evaluated geometric error. This criterion directly attempts to cut down the systematic downward bias mentioned earlier. However, when  $\hat{y}_{j^*k}$  is not greater than half the evaluated geometric error at step  $k-1$ , the criterion is not so interesting any longer – one may expect that the point will fall inside the tolerance zone defined in the former step. Thus we adopt a composite rule (*Switch*) which switches from *MaxtInc* to an informative criterion if the maximum expected increase is not positive. We use a composite informative criterion which

blends the objective of reducing prediction uncertainty with the objective of not leaving wide areas of the domain unexplored. According to this criterion the winning candidate is the one maximizing the product between prediction variance and the distance of the candidate from the nearest design point. This can be regarded as a *weighted MaxVar* criterion (*MaxWVar*) where weights favor areas with a lower density of design points. The next site is selected by:

$$x_{n_0+k} = c_{j^*k}, \quad j^* = \operatorname{argmax}_{1 \leq j \leq M-k} \operatorname{Var}(\hat{y}_{jk}) d_{jk} \quad (9)$$

$$d_{jk} = \min_{\substack{1 \leq j \leq M-k \\ 1 \leq i \leq n_0+k-1}} \operatorname{dist}(c_{jk}, x_i)$$

where operator “dist” computes the Euclidean distance so that  $d_{jk}$  is the distance between the  $j^{\text{th}}$  candidate at step  $k$  and the design point nearest to it.

Next-point selection is the start of the cyclic part involving, in the order, observation at the new site, alignment of the present point cloud, evaluation of the local and global geometric error, and re-estimation of the Kriging model using also the added point. In the case-studies the procedure is stopped at the step  $k = K$  when the plan has reached the maximum size  $n_0 + K$ . However, in general, more suitable stopping rules might be adopted.

## CASE STUDY

The considered case study involves the free-form surface of an helicopter component defined by a NURBS spline. The component has been measured on 568 points (about one point every 100 mm<sup>2</sup>). This set coincide with the initial candidate sets in the simulated procedure. Moreover, the geometric error evaluated considering this point cloud has been considered as reference geometric error value for the evaluation of the performance of the proposed methodology (the actual value is 0.549 mm). To align the cloud of points to the nominal surface the algorithm described by Zhu *et al.* [11] has been implemented. To define the point-to-point distance, which is required for Kriging computation, the nominal  $u, v$  spline parameters have been associated to every point. These coordinate are expressed in [mm]; therefore, the distances for the computation of matrix  $R(\theta)$  are the distances between points computed along the nominal surface. Figure 3 shows the local form error, i.e. the residual surface after the nominal surface has been subtracted. As one

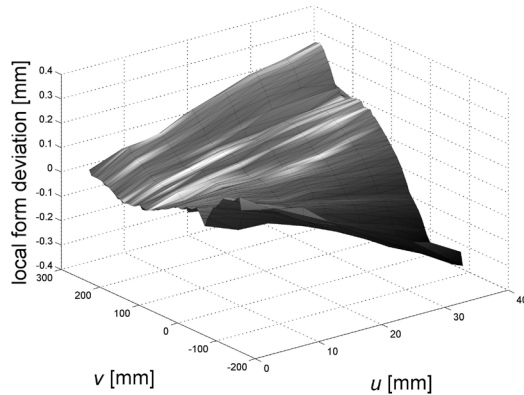


FIGURE 3. Local form error plot.

may see, the form error presents a quite smooth behavior, which can be efficiently fitted by Kriging.

The adaptive method has been developed by integrating the *Matlab* and *R* packages via the *Matlab-R link* [12]. The *R* software has been used for building the Kriging models [13].

The initial sampling pattern is a 8 points Latin Hypercube Sampling (LHS) design, which guarantees a reasonably uniform coverage of the surface. A genetic optimization algorithm (available in the *R* package) has been used for the non linear ML estimation of the correlation parameters and the process variance. The initial guess for starting the optimization is the average of one hundred parameters estimates provided by as many optimization runs with a random initial guess. In the estimation of the Kriging models needed for computing the Jackknife variance the initial guess for correlation function parameters is their value obtained with the full set  $S_k$ . Computing time for running a single step of the procedure is compatible with real time operations on the CMM.

Adaptive strategy results have been compared to those one may obtain with standard LHS design. Results of the application of the adaptive procedure to the case study, in terms of accuracy of the estimated geometric error vs. the number of added points, are plotted in Figure 4. Accuracy is defined as the ratio between the geometric error computed by the adaptive procedure and the error computed from all measurements in the dataset. Forty-two added points are considered ( $K = 42$ ) leading to a maximum design size,  $n_0 + K$ , of 50. Lines refer to the mean

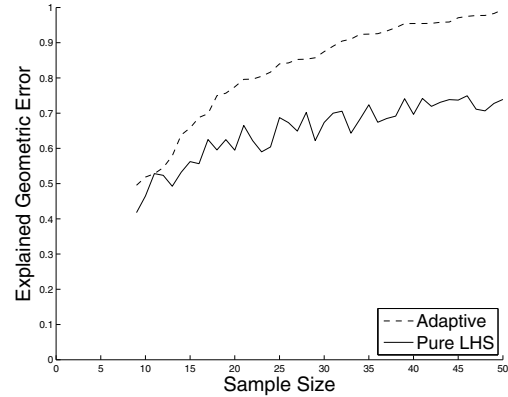


FIGURE 4. Accuracy of the estimated geometric error (% of the true error) versus the number of measured points. The lines refer to the mean error over 30 replicated plans.

error over 50 replicated plans. Replications are needed because the MLE optimization result is subject to variability due to the random choice of the initial guess of the optimization algorithm (recall that MLE is needed also in the computation of the Jackknife variance). Notice the monotonic increase of accuracy. The adaptive method is able to get nearly the 100% accuracy with about fifty points, while the standard LHS strategy stops around 65%. The intrinsic randomness of the point pattern in a LHS strategy is the reason for which its accuracy increase is not perfectly monothonic with the sample size.

Figure 5 aids the understanding of how the algorithm behaves. It shows how the surface fitted by Kriging changes as the sample size increases (matte surface), compared to the real measured points (transparent surface). It is apparent that, as the sample size increases, the fitted surface approaches the real surface thus allowing the identification of the most deviating point.

## CONCLUSIONS AND FUTURE WORK

In this paper an adaptive sampling strategy for geometric tolerance verification has been proposed. The strategy is based on a Kriging fitting of the local geometric error estimated on a small point sample. Basing on this fitting, and on two criteria (one specific for the considered problem and one informative more generally applicable when Kriging fitting is involved), the algorithm is able to identify which points have to be sampled to incur in the most deviating areas of the measured feature. A previous work [9] showed that the algorithm is effective when the tolerance is completely

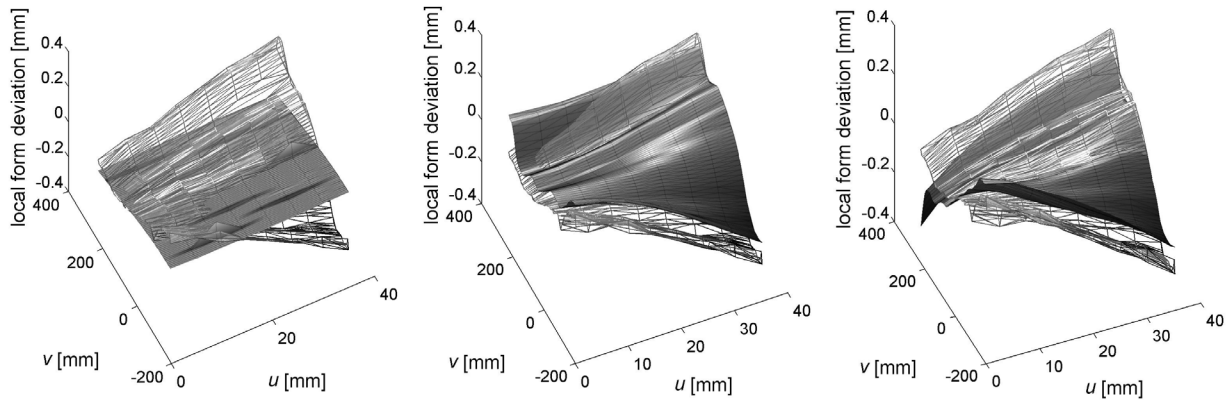


FIGURE 5. Kriging fittings as the sample size increases. From left to right: 8 points, 27 points, 50 points.

constrained by a datum system; this work extends its applicability to generic, unconstrained profile tolerances. In general the proposed methodology is able to reduce the measurement uncertainty in the evaluation of profile error, given the sample size.

Future research will involve both an improvement of the methodology and the extension to different applications. As for the first objective we will consider:

- a study of the effect of the type of the initial plan and its size,
- the evaluation of different correlation functions, the use of the knowledge of the nominal geometry of the surface to tune the parameters of the correlation function,
- the study of new criteria for next-point selection trying to find the best match between the criterion and the particular objective of the application,
- the comparison with the case implementing the “Kriging variance” in the place of empirical variance estimates, like the one based on Jackknife which is used here,
- the use of limit Kriging to avoid the “extrapolation” problem in the computation of the Jackknife variance,
- dynamic criteria to choose the candidates sites, opposed to the static one used in this paper,

- a scrutiny of different stopping rules.

As for the extension to other metrological applications, we will explore the potential of the method in the case of measurements made with non-contact optical devices, like, for example, measurements of roughness and profile based on white-light interferometry. These devices produce very accurate measurements but on a very small area of the testpiece, so that efficient sampling over the surface is mandatory.

## ACKNOWLEDGMENTS

This work was partly supported by the Italian Ministry for Education, University and Research (MIUR) under the project PRIN 2008 “Innovative geometrical control: efficiency, globalization and robustness for the quality of the Italian manufacturing industry”.

## APPENDIX

An empirical measure of the variance of Kriging predictions is provided via cross-validation and jackknife. At the step  $k$ ,  $k = 0, 1, 2, \dots, K$ , observations are available at each of the  $n_0 + k$  design sites  $x_i$ ,  $i = 0, 1, 2, \dots, n_0 + k$ , forming the point set:

$$S_k = \{(x_1, y_1), \dots, (x_{n_0+k}, y_{n_0+k})\} \quad (10)$$

By eliminating one point at a time from  $S_k$  one obtains  $q = n_0 + k$  subsets of the form:

$$S_k^{(-i)} = \{(x_1, y_1), \dots, (x_{i-1}, y_{i-1}), (x_{i+1}, y_{i+1}), \dots, (x_{n_0+k}, y_{n_0+k})\} \quad (11)$$

with  $i = 1, 2, \dots, q$ . Basing on each  $S^{(-i)}$  subset the Kriging parameters are estimated by Maximum Likelihood and the response is predicted at each of the candidate sites  $c_{jk}, j = 1, 2, \dots, M - k$ . Let  $\hat{y}(c_{jk})^{(-i)}$  denote such predictions and  $\hat{y}(c_{jk})$  the prediction at  $c_{jk}$  based on the whole set  $S_k$ . Then the *pseudo-values* are computed at any candidate  $c_{jk}, j = 1, 2, \dots, M - k, k = 0, 1, \dots, K$ , by:

$$\begin{aligned}\tilde{y}(c_{jk}) &= q\hat{y}(c_{jk}) - (q-1)\hat{y}(c_{jk})^{(-i)} \\ j &= 1, 2, \dots, M - k, \\ k &= 0, 1, \dots, K, \\ i &= 1, 2, \dots, q\end{aligned}\quad (12)$$

The estimated *jackknife variance* of the prediction at the candidate site  $c_{jk}$  at step  $k$  is:

$$\hat{s}_{jk}^2 = \frac{1}{q(q-1)} \sum_{i=1}^q \left( \tilde{y}(c_{jk})^{(-i)} - \bar{\tilde{y}}_{jk} \right)^2 \quad (13)$$

where  $\bar{\tilde{y}}_{jk} = \frac{1}{q} \sum_{i=1}^q \tilde{y}(c_{jk})^{(-i)}$ .

## REFERENCES

- [1] Government, and Industry Data Exchange Program; 1988. Alert No.11A8801.
- [2] ASME. ASME Y14.5M-2009: Dimensioning and Tolerancing -Engineering Drawing and Related Documentation Practices. New York; 2009.
- [3] Moroni G, Petrò S. Geometric tolerance evaluation: A discussion on minimum zone fitting algorithms. Precision Engineering. 2008;32(3):232–237.
- [4] Dowling MM, Griffin PM, Tsui KL, Zhou C. Statistical Issues in Geometric Feature Inspection Using Coordinate Measuring Machines. Technometrics. 1997;39(1):3–17.
- [5] Edgeworth R, Wilhelm RG. Adaptive sampling for coordinate metrology. Precision Engineering. 1999;23(3):144–154.
- [6] Badar MA, Raman S, Pulat PS. Intelligent Search-Based Selection of Sample Points for Straightness and Flatness Estimation. Journal of Manufacturing Science and Engineering. 2003;125(2):263–217.
- [7] Obeidat S, Raman S. An intelligent sampling method for inspecting free-form surfaces. The International Journal of Advanced Manufacturing Technology. 2009;40:1125–1136.
- [8] Pedone P, Vicario G, Romano D. Kriging-based sequential inspection plans for coordinate measuring machines. Applied Stochastic Models in Business and Industry. 2009;25(2):133–149.
- [9] Ascione R, Moroni G, Petrò S, Romano D. Adaptive inspection plans in coordinate metrology based on Gaussian Process models. In: Proceedings of the 10th annual conference of the European Network for Business and Industrial Statistics. Antwerp, Belgium: ENBIS; 2010. p. CD-ROM.
- [10] Kleijnen JPC, van Beers WCM. Application-driven sequential designs for simulation experiments: Kriging metamodeling. Journal of the Operational Research Society. 2004;55(8):876–883.
- [11] Zhu L, Xiong Z, Ding H, Xiong Y. A Distance Function Based Approach for Localization and Profile Error Evaluation of Complex Surface. Journal of Manufacturing Science and Engineering. 2004 Aug;126(3):542–554.
- [12] Henson R. MATLAB R-link; 2004. Available from: <http://www.mathworks.com/matlabcentral/fileexchange/5051>.
- [13] Roustant O, Ginsbourger D, Deville Y. DiceKriging: Kriging methods for computer experiments; 2010. R package version 1.0. Available from: <http://CRAN.R-project.org/package=DiceKriging>.



# CREATING FUNCTIONAL SURFACE STRUCTURES BY MILLING USING SELF-EXCITED TOOL VIBRATIONS

Dirk Biermann<sup>1</sup>, Tobias Surmann<sup>1</sup>, Sven Odendahl<sup>1</sup>,  
Markus Steiner<sup>1</sup>, Rouven Hense<sup>1</sup>, and Sascha Rausch<sup>1</sup>

<sup>1</sup>Institute of Machining Technology  
TU Dortmund  
Dortmund, Germany

## INTRODUCTION

Applying surface structures on a forming tool is a valid approach to control the material flow during a forming process [1]. This is especially useful in the newly developed combination of sheet metal forming and bulk metal forming, called sheet-bulk metal forming, which is investigated in the Transregional Collaborative Research Center 73. Functional surface structures can be applied after the milling process using different techniques, like grinding or blasting. An alternative method presented in this abstract is to use self-excited tool vibrations, also called chatter, to create these structures directly during the milling process. Normally, chatter is avoided to prevent damage to the tool and to generate a smooth surface, but for the structuring of surfaces this provides the possibility to reduce the number of process steps and to generate surface structures, which are smaller than the applied tool.

Although it is not possible to design a specific functional surface structure and afterwards replicate it with this method, several kinds of structures are manufacturable by utilizing different tools, cantilever lengths, and varying process parameters. A proprietary simulation system is used to predict promising process-parameter ranges and surface structures and, therefore, to ultimately save machining time and raw materials. After having previously shown the general applicability of the approach using aluminum as workpiece material [2], in these investigations the procedure is extended to tool steel C45E (1.1191) with additional regard to tool wear.

## SIMULATION SYSTEM

The simulation system for the modeling of surface structures generated by a milling process with chatter consists of three different simulation components. The first component performs the task of simulating the milling process as accurately as possible to calculate the forces acting on the milling tool. This is accomplished by modeling the

tool and the local workpiece section in proximity of the tool using a technique called Constructive Solid Geometry (CSG). With this technique, even complex objects can be modeled as Boolean combinations of basic shapes, like sphere, torus, or cylinder. The current workpiece corresponds to the Boolean difference of unmachined part and union of the tool models at all prior tool positions. In the same way the undeformed chip shape is obtained, and by casting rays through this model, the input values for the force calculation using the Kienzle equation can be determined [3].

The modeling of the dynamic behavior of the complete machine system is essential for the investigation of surface structures generated during a milling process [4]. There are different approaches to accomplish this including finite-element and multi-body simulations [5]. A very efficient way to simulate the dynamic behavior is to use a system of harmonic oscillators, which reproduces the frequency response function of the system consisting of tool and machine. The oscillator parameters are determined using an evolutionary algorithm. Often, it is sufficient to use only one oscillator replicating the first eigenfrequency of the tool. The system is fed with the forces calculated by the milling simulation so that the deviation of the tool from the programmed tool path can be evaluated for any position [6].

The actual surface of the workpiece is modeled by a high-resolution dixel board representing a small section of the workpiece. The cutting edge is modeled as a parametric curve so that the surface of the sweep volume can be generated as a triangulated mesh. Using the tool positions determined by the milling simulation module adjusted by the tool deflections calculated with the system of harmonic oscillators, the actual cutting positions can be determined accurately. By applying rasterization techniques from the field of computer graphics, these can be projected directly into the dixel board [7].

## EXPERIMENTAL INVESTIGATIONS

In the experiments, several test workpieces were machined on a Grob BZ 40 CS machining center. To obtain a catalog of possible surface structures, six patches with different process parameters were milled on each 10 mm x 8 mm C45E block. Two different types of toroidal cutter were used with three teeth, a diameter of 8 mm and a cantilever length of 58 mm each, and cutting edge radii of 2.5 mm and 3 mm. The milling strategy was downmilling while varying the axial immersion between 0.1 mm and 0.5 mm and the radial immersion between 1 mm and 3 mm. The feed per tooth was kept constant during all experiments at 0.12 mm with spindle speeds ranging from 15,000 rpm to 23,000 rpm.

All patches, which were planned to be manufactured with tools with a cutting edge radius of 3 mm, could be produced with the same tool without any visible chipping. In contrast, three tools with 2.5 mm cutting edge radius had to be used to machine the same amount of patches. Therefore, this abstract focuses on the structures produced with the former tool type. The surfaces

were measured using a confocal white-light microscope. Fig. 1 gives an overview of some interesting surface structures obtained with different process parameters. This illustrates the diversity of structures, which are possible by milling with intentionally invoked chatter. The structures differ not only in roughness, but also exhibit different kinds of shapes, like ovals, crescent shapes or simple lines for the cavities, and pyramids and wave-like shapes for the peaks. Different forms of overlap between these shapes depending on the process parameters result in an even greater diversity of possible structures. Those patterns seem to be random at first, but as will be shown in the next section, they are in fact to a certain extent deterministic and reproducible by the simulation system. The individual elements in this set of manufacturable topographies can be classified according to several criteria. The first criterion, which is important with regard to the control of the material flow, is the symmetry and the direction of the structures. Other criteria include the ratio between peaks and cavities, and the continuity or noncontinuity of the patterns.

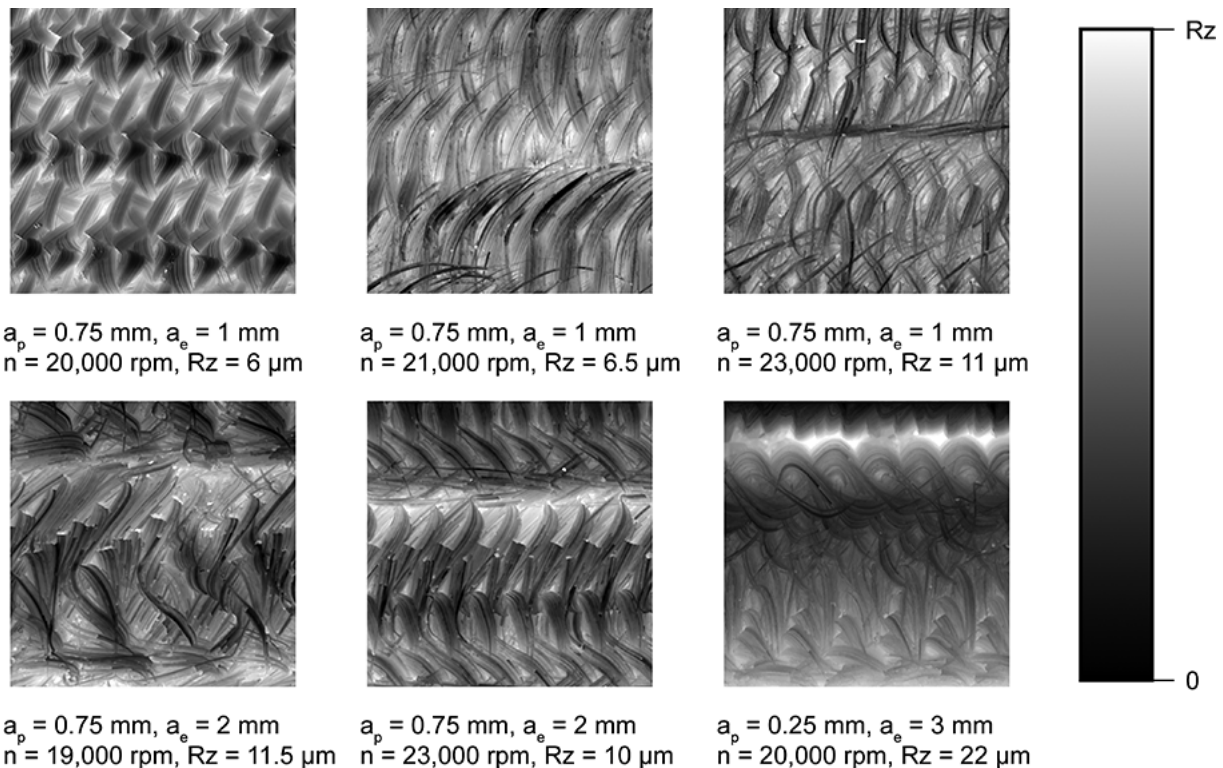


FIGURE 1. False-color white-light microscope images of a 0.28 mm x 0.28 mm area of selected surface structures.

Additional workpiece blocks were used to examine the tool wear while milling a complete block with constant engagement conditions. Using an axial immersion of 0.75 mm and a radial immersion of 1 mm at a spindle speed of 20,000 rpm produced the best result. With these parameters, it was possible to machine a whole test block with the same tool without significant tool wear. However, the surface structure on this block changes slightly during the process. Especially after the run-in phase of tool, there is a visible change in structure. This has to be investigated in more detail in the future so that a uniform structuring of larger surface areas is possible.

### COMPARISON OF SURFACE STRUCTURES FROM SIMULATION AND EXPERIMENT

For the simulation of the surface structures, first, the coefficients for the force calculation have to be determined. This can be done by conducting a few simple experiments and then fit the simulation to the experiment data. These parameters can also be used later for similar tools and the same workpiece material. Additionally, the modal parameters for the modeling of the dynamic behavior are necessary. In this case, it was sufficient to use one harmonic oscillator

whose parameters were identified by compiling a stability chart and again fit the simulation to the experiment data to calculate eigenfrequency, model mass, and damping factor.

A few results of the simulation and the surface structures obtained by the corresponding experiments are compared in Fig. 2. Even though there is no exact match between simulation and experiment, the general appearance of the topographies is consistent. In both structures on the left, the shape of the peaks is very similar, and the small grooves in the structure can also be found on both images. At first glance, there is a bigger discrepancy between simulation and experiment for the structure in the middle. However, the crescent-shaped cavities are present in simulation and experiment. They are just less distinct in the structure originating from the real process. Even the distribution of the small peaks is in accordance with the experiment. The structure on the right also seems to show little correlation at first since the crescent-shaped cavities do not exist in the image from the simulation, but the long continuous peaks match. Additionally, the smaller grooves exhibit a pattern similar to the one from the experiment.

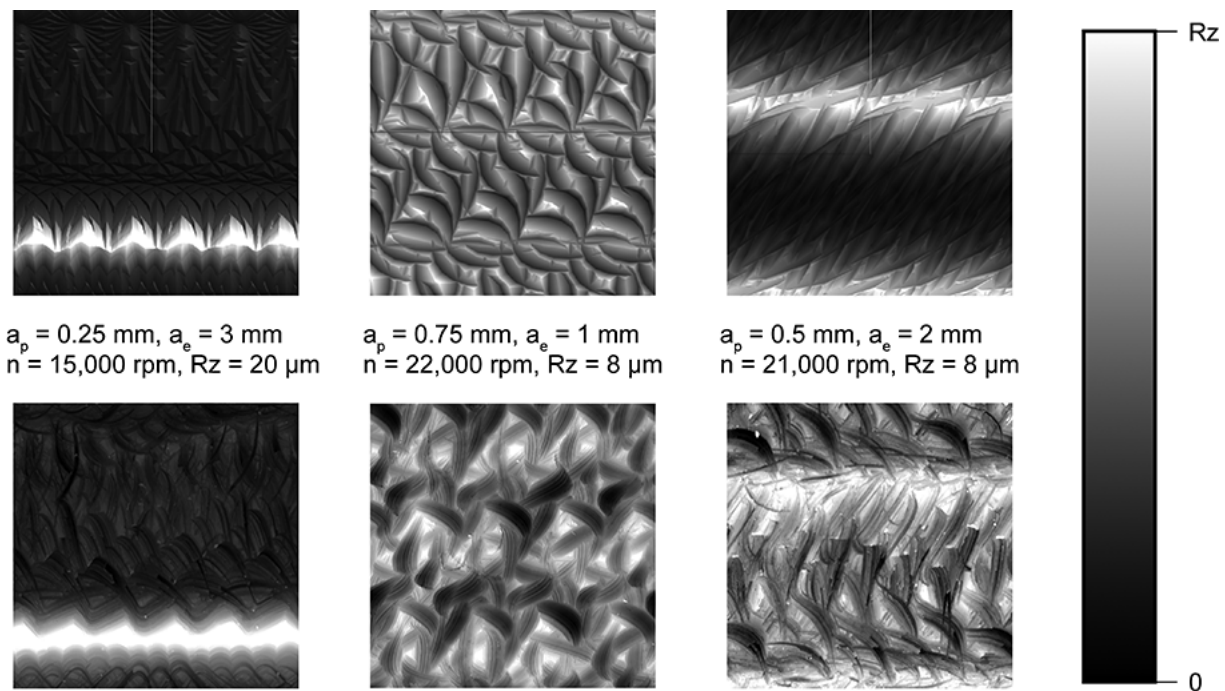


FIGURE 2. Comparison of surface structures generated by the simulation (top) and by the actual milling process (bottom).

## CONCLUSION AND OUTLOOK

In this abstract, the individual components of a simulation system for the modeling of surface structures and the implemented modeling techniques were described. The interaction of those components combined with several optimization techniques allows an efficient simulation of the process so that it is possible to conduct simulation runs over the whole process-parameter range before the actual machining process. Additionally, results of the experimental investigations were presented. Several test workpieces were machined with multiple patches of different surface structures each. These constitute a complete systematical examination of the investigated process-parameter range and, therefore, a catalog of possible surface structures. The most interesting of these structures were presented in this abstract. In addition, a few surface structures were compared to the ones predicted by the simulation system. This validates the modeling techniques used in the simulation and shows the feasibility of a simulation-based process design.

In general, it is possible to predict a range of process parameters, in which a similar structure will occur in the real process. However, the simulation of the milling process and the modeling of the surface structures still leave room for improvements. There can still be small shifts in the process parameters between simulation and process for a certain surface structure. This will be compensated in the future by conducting a sensitivity analysis during the investigation of promising process-parameter ranges. In addition, the model of the structure itself can be improved by further enhancing the modeling of the cutting edge. Furthermore, to gain insight into the advantages of the individual structures, the surface structures will be analyzed tribologically in cooperation with other projects of the TR 73. This will also give an indication, for which structure types additional variations should be investigated. Another important challenge is the structuring of larger surface areas. There are influences that might change during the course of the process, e.g., tool wear. This has to be compensated to get a uniform surface structure.

## ACKNOWLEDGMENTS

This work is based on investigations of the Transregional Collaborative Research Center TR 73, which is kindly supported by the German Research Foundation (DFG).

## REFERENCES

- [1] Bruzzone AAG, Costa HL, Lonardo PM, Lucca DA. Advances in engineered surfaces for functional performance. *CIRP Annals – Manufacturing Technology*. 2008; 57 (2): 750-769
- [2] Biermann D, Surmann T, Odendahl S, Brüggemann T, Krebs E. Surface Structuring by Milling with Intentionally Invoked Chatter. In: Altintas Y, Denkena B, Brecher C, editors. *Proceedings of the CIRP 2nd International Conference Process Machine Interactions*; 2010 Jun 10-11: Vancouver, BC, Canada: University of British Columbia; 2010. M15.1-10.
- [3] Surmann T, Kalveram M, Weinert K. Simulation of Cutting Tool Vibrations for the Milling of Free Formed Surfaces. In: Neugebauer R, editor. *Proceedings of the 8th CIRP International Workshop on Modeling of Machining Operations*; 2005 May 10-11: Chemnitz, Germany: Verlag Wissenschaftliche Scripten; 2005. 175-182.
- [4] Altintas Y. *Manufacturing Automation: Metal Cutting Mechanics, Machine Tool Vibrations, and CNC Design*. Cambridge University Press; 2008.
- [5] Altintas Y, Brecher C, Weck M, Witt S. Virtual Machine Tool. *CIRP Annals – Manufacturing Technology*. 2005; 54 (2): 115-138
- [6] Surmann T, Biermann D, Kehl G. Oscillator Model of Machine Tools for the Simulation of Self Excited Vibrations in Machining Processes. In: Denkena B, editor. *Proceedings of the 1st International Conference on Process Machine Interactions*; 2008 Sep 03-04: Hannover, Germany: PZH Produktionstechnisches Zentrum GmbH; 2008. 23-29.
- [7] Weinert K, Surmann T, Müller, H. Modeling of Surface Structures Resulting from Vibrating Milling Tools. *Production Engineering – Research and Development*. 2006; XIII (2): 133-138



# NANO/MICRO MACHINING USING MULTI-ARRAYED TOOL FOR NANO/MICRO SURFACE PATTERNING

Soochang Choi<sup>1</sup>, Sang-min Lee<sup>1</sup>, Lu Hong<sup>1</sup>, Jong-Kweon Park<sup>2</sup> and Deug Woo Lee<sup>3</sup>

<sup>1</sup>Department of Nano Fusion Technology  
Pusan National University

Miryang, Gyeongsangnam-do, South Korea

<sup>2</sup>Intelligent Manufacturing System Division  
Korea Institute of Machinery & Materials (KIMM)  
Daejeon, KOREA

<sup>3</sup>Department of Nano-Mechatronics  
College of Nanoscience and Nanotechnology, Pusan National University  
Miryang, Gyeongsangnam-do, South Korea

## 1. INTRODUCTION

Various surface areas with nano/microscale patterns or shapes may exhibit phenomena such as the lotus effect. A considerable amount of research has been conducted to find practical applications of such phenomena. In order to apply a pattern, it is necessary to develop technologies for measuring the natural objects and analyzing the measured phenomena, as well as for the design and fabrication of the pattern itself.

Figure 1 shows typical pattern for analysis of superhydrophobic [1]. Also, Silk et al. [2] studied the impact of structured surfaces on spray cooling and demonstrated that enhanced surfaces provide larger heat transfer relative to smooth surfaces. They examined three geometries structured with cubic pin fins, pyramids and straight fins (Figure 2) made of oxygen-free high conductivity copper and used Fluorinert PF-5060 as the working fluid. These patterns are general pattern for smart surface.

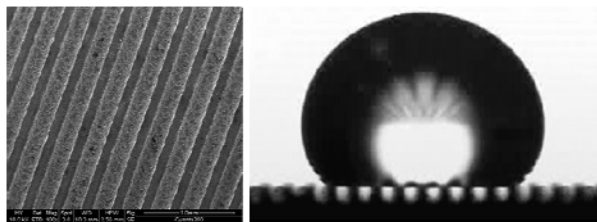


FIGURE 1. Micro pattern for superhydrophobic [1]

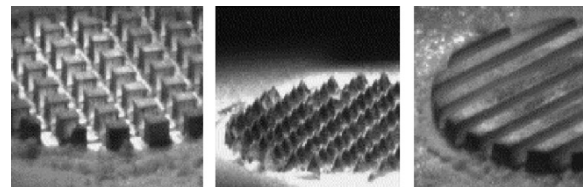


FIGURE 2. Surface structures examined by Silk et al. [2]

Various methods are employed to fabricate a pattern designed from the measurement results and pattern analysis. Representative techniques include the microelectromechanical system (MEMS) process, and a technology to make micro pattern using Lithography being used for the semiconductor process [3], processing technology using electron beam [4], or using laser beam [5], etc. In addition, those technologies using electric discharge such as EDM, ECM, WEDM [6-8], etc. are often used. Imprint technology [9-10] to be used for mass production of pattern is also actively applied today.

The MEMS process is used to fabricate pattern masters for mass production. However, it is complex and difficult to apply to a large area. On the other hand, as a fabrication technology, imprinting and hot embossing is suitable for mass production, but presents other problems, such as difficulty changing the pattern and its inapplicability to certain materials, metals in particular.



Mechanical micro-processing methods are being studied to resolve the problems associated with the aforementioned processes. Although mechanical processing offers such advantages as the ability to fabricate various patterns from a variety of materials, it is also hampered by extremely low productivity because of its use of a single tool. To solve this problem, a technology for fabricating multiple arrays of diamond tips has been studied [11]. However, there are difficulties when mold fabrication via the MEMS process and high-energy deposition are used to create these multiple arrays. The objective of the present study is to fabricate multiple arrays of diamond tips in a new shape, using polycrystal diamond, which is often used for cutting tools, and to evaluate the processing performance of the fabricated tips. Thus, this paper has fabricated new shape of multi-array tips using polycrystal diamond that is often used for cutting tools and evaluated their characteristics. And we made straight line pattern and rod shape.

## 2. ANALYSIS OF MACHINING PATH USING MULTI-ARRAY DIAMOND TIPS

Figure 3 shows machining method using multi-array diamond tip. Figure 3 (a) is shaping based scratching machining using a multi array tip for straight line pattern and Figure 3 (b) is spindle based scratching machining for rod shape. The case of shaping based scratching machining it predicts the shape of pattern. But spindle based scratching machining will not be able to confirm the shape of the pattern. We need to analyse the path of scratching machining using spindle. We used Matlab for analysis of machining path using spindle. Figure 4 shows result of a machining path. The size of rod shape is  $80\ \mu\text{m}$

## 3. DESIGN OF MULTI-ARRAY DIAMOND TIPS

In this study, laser processing is used to fabricate multiple arrays of diamond tips. Figure 5 illustrates the design to be fabricated by this technique. The shape of the tip was designed with reference to the Berkovich diamond tip used to evaluate

material characteristics via nano/micro-scratch processing or press-in. The tip was designed on a  $100\ \mu\text{m}$  scale to prevent breakage that may occur during processing. Figure 6 shows appearance of the fabricated Tip attached to the actual tool shank.

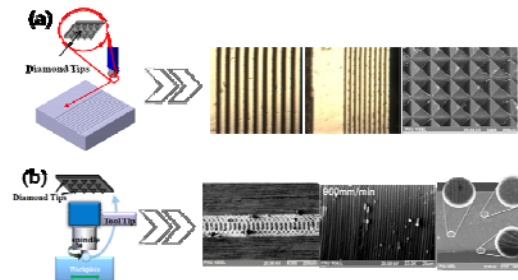


FIGURE 3. machining method using multi-array diamond tips, (a) Shaping based scratching machining using multi array tips, (b) Spindle based scratching machining using multi array tips

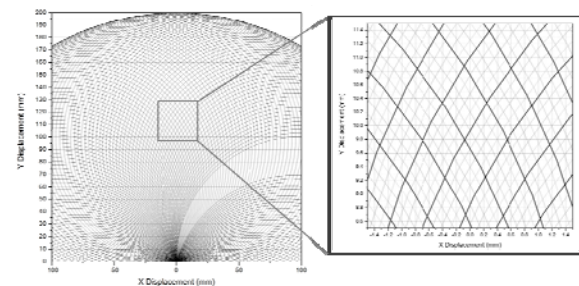


FIGURE 4. Tip Path of spindle based scratching machining

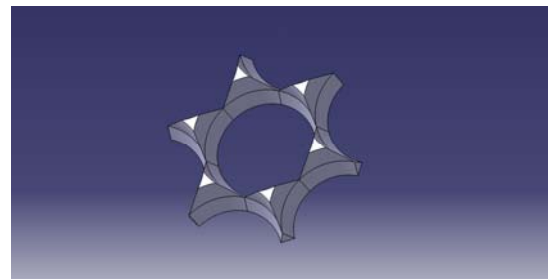


FIGURE 5. Design of multi-array diamond tips

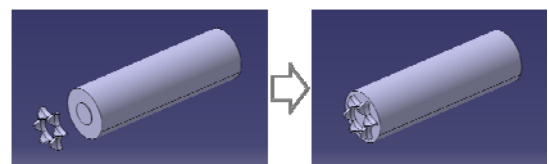


FIGURE 6. Appearance of the fabricated tip attached to the actual tool shank

#### 4. FABRICATION OF MULTI-ARRAY TIPS USING LASER

Figure 7 shows the actual laser fabrication process for multiple arrays of tips. Polycrystal diamond is usually manufactured via a sintering process on a super hardness plate. The fabricated polycrystal diamond was processed with a laser to produce tips with the desired shape. A fiber laser was employed for this purpose, and the round tips were fabricated by using a positioning system and shifting the focus of the laser. The angle between the laser and the polycrystal diamond was maintained at  $3^\circ$  during processing, which progressed in a trigonal pyramid shape. At that point, multiple arrays of diamond tip structures could be formed using the remaining part from the fabrication process. Figure 8 shows the shape of the remaining part after laser processing. Figure 9 shows appearance of laser processing.

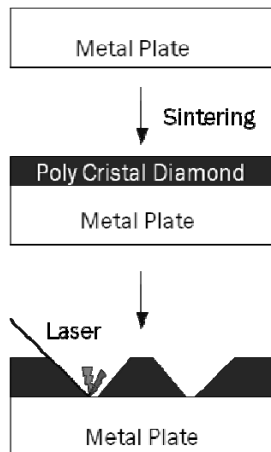


FIGURE 7. Actual fabrication processes of multi-array tips using laser

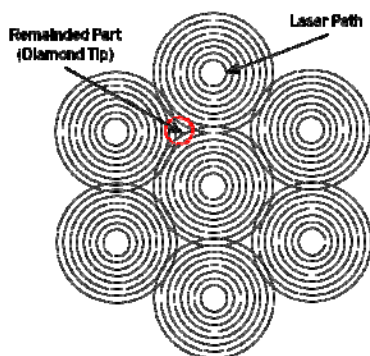


FIGURE 8. Path of laser and shape of remained part after processing

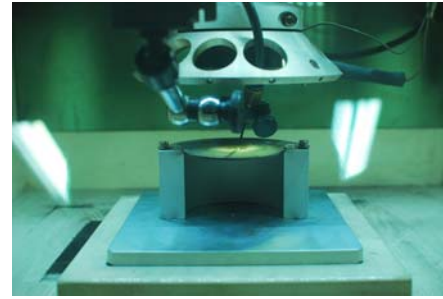


FIGURE 9. Appearance of laser processing

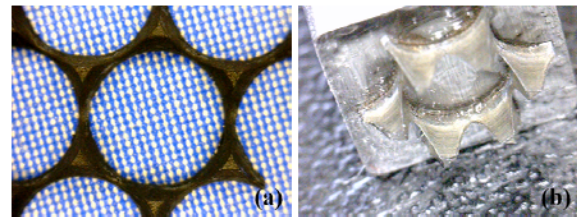


FIGURE 10. Shape of the fabricated multi-array tips, (a) Shape of the multi-array tips, (b) Appearance of fabricated multi-array tips attached on the shank.

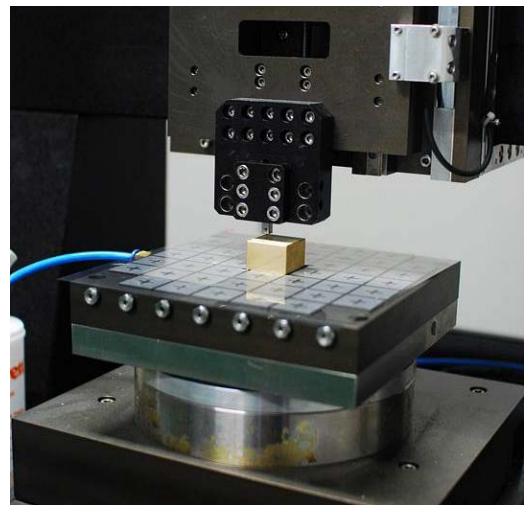


FIGURE 11 Appearance of processing test using fabricated multi-array diamond tips

#### 5. EVALUATION OF PROCESSED MULTI-ARRAY DIAMOND TIP SHAPE

The fabricated multiple arrays of tips are illustrated in Figure 10 (a) Shape of the multi-array tips, (b) Appearance of fabricated multi-array tips attached on the shank.

## 6. EVALUATION OF MULTI-ARRAY DIAMOND TIP PROCESSING PERFORMANCE

Figure 11 illustrates the processing experiment using the fabricated multiple arrays of diamond tips. Figure 12 shows a photograph of the processing results using the multiple arrays of diamond tips. Oxygen-free copper was used as the processing sample. Figure 12 (a) shows straight line pattern using shaping based scratching machining and (b) shows rod shape using spindle based scratching machining.

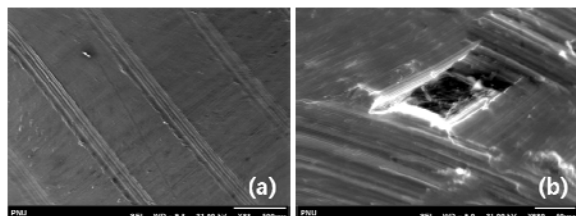


FIGURE 12. Machined sample using the multi-array diamond tips

## 7. CONCLUSIONS

This study was concerned with the fabrication of multiple arrays of diamond tips to be utilized for the micro-processing of nano/micropatterns. The multiple arrays were fabricated via laser processing. As a result of this study, we have found that it is possible to process arrays of tips using a laser, and patterns using the processed tips. We intend to fabricate more precise tips to enable micropattern processing.

## ACKNOWLEDGEMENT

This work was supported by NCRC (National Core Research Center) program of the Ministry of Education, Science and Technology (2010-0008-277) and "Development of Multi - Physics - Based Micro Manufacturing (MP-M2) Technologies for Biomedical Products" International Collaborative R & D Program of ministry of knowledge economy.

## REFERENCES

[1] R. Kannan, D. Sivakumar, "Drop impact process on a hydrophobic grooved surface", *Colloids and Surfaces A: Physicochem. Eng. Aspects*, 317, 694-704, 2007.

[2] A.A.G. Bruzzone, H.L. Costa b, P.M. Lonardo, "Advances in engineered surfaces for functional performance" *CIRP Annals Manufacturing Technology* 57, 750 -769, 2008

[3] R.A. Lawes, "Future trends in high-resolution lithography", *Applied Surface Science*, 154-155, 519-526, 2000.

[4] Tadahiro Takigawa, Katsuhiro Kawabuchi, Makoto Yoshimi and Yoshihide Kato, "High voltage electron beam lithography", *Microelectronic Engineering* 1, 121-142, 1983.

[5] Avanish Kumar Dubey, Vinod Yadava, "Laser beam machining—A review", *International Journal of Machine Tools & Manufacture* 48, 609-628, 2008.

[6] K.H. Ho, S.T. Newman, S. Rahimifard, R.D. Allen, "State of the art in wire electrical discharge machining (WEDM)", *International Journal of Machine Tools & Manufacture* 44, 1247-1259, 2004.

[7] K.H. Ho, S.T. Newman, "State of the art electrical discharge machining (EDM)", *International Journal of Machine Tools & Manufacture* 43, 1287-1300, 2003.

[8] B. Bhattacharyya, S. Mitra, A.K. Boro "Electrochemical machining: new possibilities for micromachining", *Robotics and Computer Integrated Manufacturing* 18, 283-289, 2002.

[9] H. Schmitt, M. Rommel, A.J. Bauer, L. Frey, A. Bich, M. Eisner, R. Voelkel, M. Hornung, "Full wafer microlens replication by UV imprint lithography", *Microelectronic Engineering*, 87, 1074-1076, 2010.

[10] Keisuke Nagato, Shuntaro Sugimoto, Tetsuya Hamaguchi, Masayuki Nakao, "Iterative roller imprint of multilayered nanostructures", *Microelectronic Engineering* 87, 1534-1545, 2010.

[11] JeongWoo Park, Chae Moon Lee, Soo Chang Choi, Yong Woo Kim and DeugWoo Lee. : "Surface patterning for brittle amorphous material using nanoindenter-based mechanochemical nanofabrication" *NanoTechnology*, Vol.19, 085301, 2008.

# GEOMETRICAL ANALYSIS OF SURFACE FINISH BY ULTRASONIC VIBRATION ASSISTED GRINDING

M. F. Ismail<sup>1</sup>, K. Yanagi<sup>2</sup>, and H. Isobe<sup>2</sup>

<sup>1</sup>Faculty of Mechanical Engineering

Universiti Teknologi MARA

Shah Alam, Selangor, Malaysia

<sup>2</sup>Department of Mechanical Engineering

Nagaoka University of Technology

Nagaoka, Niigata, Japan

## 1. INTRODUCTION

Ultrasonic vibration assisted grinding (UVAG) coupled with electroplated diamond abrasive tool was proposed to replace the manual polishing for mirror finish which can tremendously reduce the lead time of steel mold fabrication in plastic injection molding industry [1]. Previous study on the UVAG was focused on finding optimum grinding and pre-process condition but the problem in the process repeatability undermined its potential. The electroplated diamond abrasive tool has undetermined cutting edges and the most uncertain element in the UVAG. Hence, it is necessary to clarify the effect of the tool to the process repeatability.

The information related to the interaction between tool and work surface during the grinding process can be used to improve the process. Areal surface characterization may deliver better information from the topography. At the moment there is no standard available for areal characterization in relation to measurement and characterization condition. Characterization conditions based on the surface topography alone [5] may not suitable for comparison purpose. A common characterization condition is required for comparing work surfaces which ground with common grinding condition.

The objectives of this study are as follows.

1. To proposed characterization condition for the work surface topography for UVAG process assessment using areal method based on the machining condition.
2. To clarify the tool effect on the process repeatability.
3. To identify useful tool-work interaction information from the work surface.

## 2. SURFACE CHARACTERIZATION FOR PROCESS ASSESSMENT

In this study, surface characterization based on areal method is employed to assess the performance of the UVAG coupled with electroplated diamond abrasive tool. UVAG is performed using NC vertical milling machine with ultrasonic vibration source built in the main spindle.

### 2.1 Size of Evaluation Area

The minimum size of measuring area is determined from the machining condition by assuming the pattern of cutting marks is periodic. At first, the sampling length  $l_s$  is considered, which is equivalent to the cut-off wavelength  $\lambda_c$  for separating roughness profile and waviness from measured profile. Referring to Figure 1, the tool path has two main movements, tool feeding along  $x$  axis and tool cross feed along  $y$  axis. The tool feeding is controlled by the feed rate  $F$ , while tool cross feed is controlled by the cross feed  $P$ . Assuming the tool is single cutting edge in linear cutting, there will be a repeating cutting marks on a single line along  $y$  axis for every length equivalent to the cross feed  $P$ .

Regarding the repeating pattern along  $x$  axis, the tool feed rate  $F$  and spindle rotational speed  $S$  is considered. Since the tool is rotating while being moved along the  $x$  axis, the tool cutting marks is expected to be complicated but to simplify the matter, the maximum length of tool travelling distance in one rotation is selected to be the repeating length  $d_x$  which is the proportion of feed rate  $F$  to spindle speed  $S$  as shown in equation 1.

$$d_x = F / S \quad (1)$$



Since the roughness is defined as the higher frequency component of surface texture [6], in this study, the smaller value between  $P$  and  $d_x$  is selected to be the basis to determine the sampling length. Considering the value of  $P$  and  $d_x$  is equivalent to mean spacing between surface features  $RSm$ , similar approach to determine sampling length as in [5] is employed. Therefore, the sampling length  $l_s$  is 5 times the smaller value between  $P$  and  $d_x$ ; equation 2.

$$l_s = \min\{5P, 5d_x\} \quad (2)$$

The minimum side length of the evaluation area is 5 times of the sampling length  $l_s$  which is consistence to ISO 4288: 1996 [5].

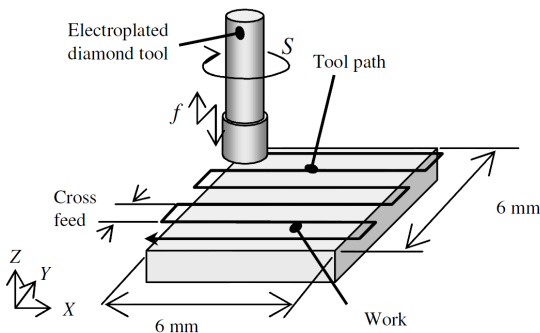


FIGURE 1. Cell size and tool path

## 2.2. Roughness parameter

Roughness parameter employed for the process assessment is  $Sq$  parameter, the root mean square value of the surface departures,  $z(x,y)$  within the sampling area  $A$ .

$$Sq = \sqrt{\frac{1}{A} \iint_A z^2(x,y) dx dy} \quad (3)$$

In this study, the roughness surface and waviness surface is separated based on Gaussian filter with cut-off wavelength  $\lambda_c$  which is equivalent to sampling length  $l_s$ .

## 3. SURFACE NANO-TOPOGRAPHY ANALYSIS FOR PROCESS DIAGNOSTIC

### 3.1 Surface nano-topography analysis for process diagnostic

Spectrum analysis is a means to extract characteristic features of surface roughness profiles by transforming the profile data into frequency domain [2]. The power spectrum of the roughness profile is determined by discrete

Fourier transformation (DFT) computed with a fast Fourier transformation (FFT) algorithm. Surface topography analysis software, MountainsMap® Premium, provides a useful tool for ASPD analysis [3].

In present study, it is interesting to see the effect of ultrasonic vibration to the work surface. In case of single cutting edge, the relation between the machining condition and the ultrasonic vibration waveform on the cutting edge locus can be deduced from perimeter equation as in equation 4.

$$2\pi r = \frac{f}{S} \lambda_u \quad (4)$$

Here,  $f$  is the ultrasonic vibration frequency,  $S$  is the spindle rotational speed,  $r$  is the position of the cutting edge measured by its distant from tool rotation centre and  $\lambda_u$  is the wavelength of the waveform developed on the cutting edge locus. If the machining condition i.e.: ultrasonic vibration  $f$  and spindle speed  $S$  are known and constant, the size of  $\lambda_u$  will change with the value of  $r$ , the cutting edge location which has definite size. Therefore, the range of wavelength  $\lambda_u$  can be determined.

TABLE 1. Experimental grinding condition

|                      |                                        |             |
|----------------------|----------------------------------------|-------------|
| Machine              | NC milling machine Makino              |             |
| Spindle speed        | $S$                                    | 2000 rpm    |
| Feed rate            | $F$                                    | 500 mm/min  |
| Cross feed           | $P$                                    | 20 $\mu$ m  |
| Depth of cut         | $H$                                    | 1 $\mu$ m   |
| Area size            | 6 mm $\times$ 6mm                      |             |
| Ultrasonic vibration | Frequency $f$                          | 60kHz       |
|                      | Amplitude $a$                          | 0.5 $\mu$ m |
| Workpiece            | Steel NAK80 (DAIDO steel, HRC40)       |             |
| Coolant              | Oil mist (Unicut Jinen MFF)            |             |
| Tool truncation      | Truncation quantity 1, 2 and 3 $\mu$ m |             |

TABLE 2. Specification of electroplated diamond abrasive tools

|                |                                     |
|----------------|-------------------------------------|
| Item           | Specification                       |
| Substrate      | Ø4mm Boron Carbide cylinder         |
| Diamond grains | #100 (160 $\mu$ m average diameter) |
| Bonding type   | Nickel electroplating               |



#### 4. EXPERIMENTAL RESULT AND DISCUSSION

Table 1 shows the machining conditions are selected based on previous study by Hara et al. (2009) which are likely capable for mirror finish [4]. The machining condition is constant between tools.

Table 2 is the specification of the electroplated diamond abrasive tools used in this study. The tool working surface is the flat end surface of the cylinder coated with diamond grains. There are 9 pieces tools used in this study.

##### 4.1. Surface roughness measurement for process assessment

The selection of the characterization is based on the machining condition. The sampling length  $l_s$  is 100 $\mu\text{m}$ , equivalent to 5 times of tool cross feed  $P$ . Hence, the minimum size of evaluation area is 0.5 mm  $\times$  0.5 mm. The topography of work surface are measured at randomly selected 6 locations on the surface using white light interferometer (WLI) with 10 $\times$  Mirau objectives which provides 0.8mm  $\times$  0.65mm viewing area and 0.64  $\mu\text{m}$  lateral resolution. The viewing area is employed as the evaluation area for the surface topography characterization. Inclination of measured data is removed by plane regression based on least square method. Gaussian filtering is performed to separate roughness and waviness surface from the measured topography data with cut-off wavelength  $\lambda_c$  0.1 mm, equivalent to sampling length  $l_s$ . Figure 2 shows the typical scale limited surfaces obtained.

The  $Sq$  parameter is calculated for each scale limited surface, the roughness and waviness surfaces. Figure 3 is a plot of average of  $Sq$  parameter for each scale limited surfaces  $\mu Sq_r$  and  $\mu Sq_w$  with the error bar set with  $\pm 1$  standard deviation, to illustrate the variation within a sample and among samples. The  $Sq$  parameters from roughness and waviness surfaces showed that there are considerably large differences between samples and can be used to differentiate the samples.

##### 4.2. Analysis on nano-topography

WLI with 50 $\times$  Mirau objectives is used to capture the work surface in order to analyze the surface for process diagnostic and in this report, the measured surface is called nano-topography surface. The WLI has lateral resolution of 0.131  $\mu\text{m}$  and viewing area of 180  $\mu\text{m}$   $\times$  133  $\mu\text{m}$ .

Figure 4 shows isometric view of nano-topography from selected samples with the tool feeding is along  $x$  axis and the cross feed is descending the  $y$  axis. The effect of ultrasonic vibration has materialized as a consistence waveform pattern on the surface topography.

Figure 5 shows the APSD the nano-topography for surface elements along tool feeding direction with the horizontal axis represents wavelength and vertical axis represents the amplitude with power of two. All samples clearly show only one high spectrum for  $\lambda_u < 7 \mu\text{m}$  as shown in Figure 8 (a) and (b), except one sample. This phenomenon is accordance to Equation 4 with machining condition in Table 1.

##### 4.3. Tool-work interaction

The significant wavelength from APSD analysis is used as a parameter to characterize the tool-work surface interaction because the wavelength of the ultrasonic vibration marks is directly related the distance of the cutting edge from tool rotation centre  $r$ , as stated in equation 4. Figure 6 shows relation between  $\lambda_u$  and surface waviness  $\mu Sq_w$  with correlation coefficient  $R = 0.78$ , indicates that the distance from the tool rotation centre of the cutting edge which leaves the ultrasonic vibration marks may be one of the factors influence the surface waviness.

#### 5. CONCLUSION

The study proposed the usage of machining condition to determine the size of evaluation area for geometrical surface characterization and the usage of average power spectrum density on the work topography for searching information regarding the tool-work interaction. This proposed characterization revealed significant differences between ground surfaces. This study clarified that the electroplated diamond tool is the main cause of poor repeatability of the grinding process. The ultrasonic vibration marks captured in the high magnification measurement of the work surface provides useful information related to the tool-work interaction in the ultrasonic vibration assisted grinding coupled with electroplated diamond abrasive tool.

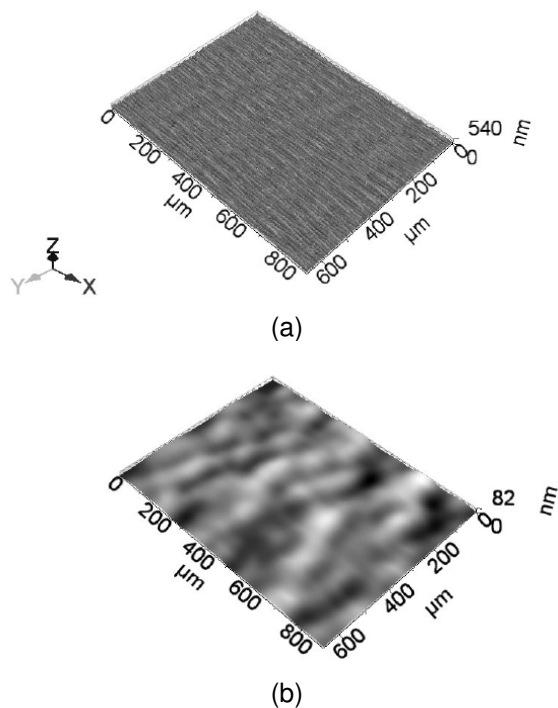


FIGURE 2. Isometric view of samples scale limited surfaces (a) roughness surface (b) waviness surface

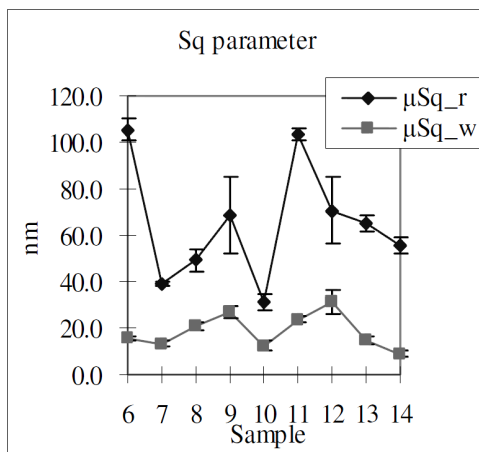


FIGURE 3. Variation of  $S_q$  parameter for scale limited surfaces

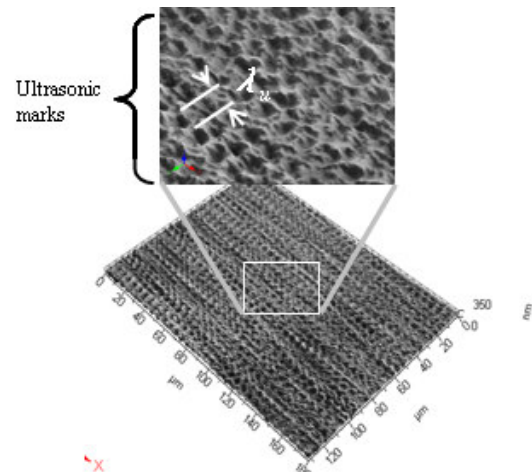


FIGURE 4. Typical nano-topography of work surface

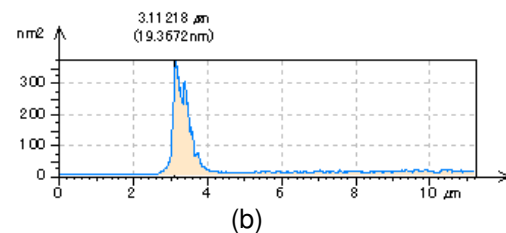
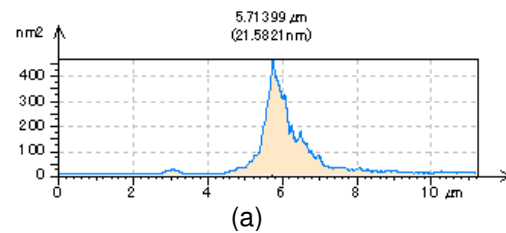


FIGURE 5. Average power spectral density of nano-topography (a) Sample 7 (b) Sample 14

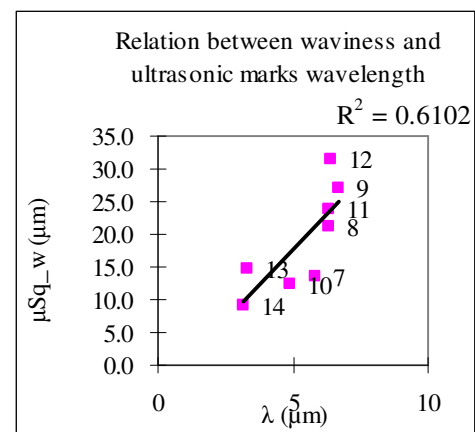


FIGURE 6. Relation between waviness parameter and wavelength of ultrasonic marks

## REFERENCES

- [1] Hara K, Isobe H, Kyusojin A, Okada M. Study on mirror surface grinding of die steel by using ultrasonically assisted diamond tools. *Int J Abrasive Technology*. 2008 1: 4: 265-273.
- [2] Cheung C F, Lee W B. A multi-spectrum analysis of surface roughness formation in ultra-precision machining. *Precision Engineering*. 2000 24: 77-87.
- [3] Digital Surf. MountainsMap® Premium 6.0.0.5740, <http://www.digitalsurf.fr/en/index.html>, assessed on July 15, 2010.
- [4] Hara K, Isobe H, Kyusojin A. Optimization of cutting edge truncation depth for ultrasonically assisted grinding to finish mirror surface. *Adv Mater Research*. 2009 76/78: 88-93
- [5] ISO 4288: 1996 Geometrical Product Specifications (GPS) -- Surface texture: Profile method -- Rules and procedures for the assessment of surface texture, International organization for standardization
- [6] Whitehouse D. Surfaces and their measurement. Hermes Penton Science. London: 2002.

# DATA ACQUISITION AND ANALYSIS OF MULTI WAVE STANDARDS

O. Jusko<sup>1</sup>, F. A. Arenhart<sup>2</sup>, H. Bosse<sup>1</sup>, G. D. Donatelli<sup>1</sup>, F. Härtig<sup>1</sup>, K. Kniel<sup>1</sup>, and M. de C. Porath<sup>2</sup>

<sup>1</sup>Physikalisch-Technische Bundesanstalt,  
Bundesallee 100, 38116 Braunschweig, Germany

<sup>2</sup>CERTI Foundation, Center of Metrology and Instrumentation,  
Campus Universitário UFSC - Setor C,  
Florianópolis – SC - CEP: 88040-970, Brazil

## GEOMETRICAL STANDARDS WITH INTENTIONAL FORM DEVIATION

In several areas of dimensional metrology geometrical standards are needed which embody not only a simple geometry like e.g. a cylinder, but additionally represent a small but relevant intentional form deviation. The main application fields for these are investigations on measurement uncertainty of coordinate (CMM) and form measurements and calibration of form measurement instruments. A well-known example for a standard of this class is the so-called “flick” standard, which embodies a ground flat at a cylinder. However, flick standards are difficult to calibrate and represent only a small wave-length band. The same is true for most other measurement standards with isolated local form deviations.

## STANDARDS WITH PERIODIC FORM DEVIATIONS

Therefore several attempts were made to overcome these limits by manufacturing measurement standards with periodic ideally sinusoidal wave structures on their surface. The idea behind this approach is to perform the analysis of measured profiles by frequency/wavelength domain analysis using methods like the (fast) discrete Fourier transform (DFT / FFT), which allows an integral evaluation of the acquired profile, not only depending on few single data points as occurs with form deviation parameters like  $RONt$  or  $STRt$  [1-4].

## MULTI WAVE STANDARDS

A simple example is a cylinder which carries one or more belts with superimposed sinusoidal waves on its inner and/or outer shell. This class of standards was proposed by Jusko et. al. [5] and called Multi Wave Standard (MWS). First MWS scanning measurements on CMMs were demonstrated in [6].

In the meantime improved types of MWS were manufactured with axial waves at the shell or wave structures at the front faces and/or combinations of both. Examples can be seen in Figures 1 and 2.



FIGURE 1. Detail of a MWS with waves at the front face and at the circumference of the cylinder.

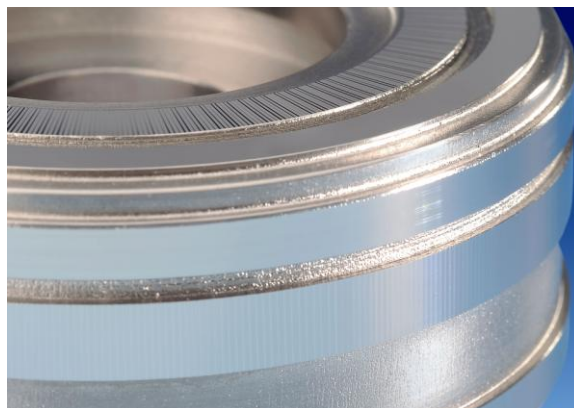


FIGURE 2. Detail of a MWS with waves at the front face and at belts at the outer and inner cylinders.

The first one (Figure 1) features waves at the front face of the standard. The waves describe closed circles around the center of the front face. The harmonic content can be measured as a straightness profile radially from the center to the outer edge. Additionally there is a belt of

harmonic waves around the measurement standard.

The second one (Figure 2) features waves at the front face whose crests extend radially. Therefore the harmonic content is embodied along a circular trace at the surface. Additionally, there are an inner and an outer belt with radial waves along the circumference of the MWS.

### INVOLUTE WAVINESS ARTIFACTS

The reliable determination of periodic micro structures of open surfaces as they exist at involute tooth flanks is of increasing importance. They allow conclusions from the waviness of the gear surface to the wear and running noise in gears. For this reason an involute waviness artifact (IWA) has been developed (Figure 3) and a new method with which it is possible to model, realise and, especially, reliably evaluate wave-shaped structures on the flank surfaces of involute cylindrical gears [7, 8].



FIGURE 3. An IWA-tooth.

In conformance with form measurement standards [3], the wavelengths were layered in a range of 2.5 mm, 8 mm and 25 mm. The amplitudes of 10  $\mu\text{m}$ , 7  $\mu\text{m}$  and 5  $\mu\text{m}$  were chosen five times larger than is to be expected in the case of running gears. The evaluation relates to a reference length of 100 mm.

### MEASUREMENT OF MULTI WAVE STANDARD PROFILES

Several challenges exist when measuring MWS form profiles. Among these are:

- The measurement profiles have to be as low-noise as possible, because noise may have significant influence to FFT-based analysis algorithms.
- The data density has to be at least 7 to 10 times the number of waves in the profile. Otherwise the wave amplitudes cannot be resolved properly. For a roundness MWS carrying a 500 UPR wave this means that at least 3500 data points should be acquired.
- An anti-aliasing filter should be installed within the signal transmission chain, before the discretization (A/D conversion) of the

profile. Its parameters should not lead to significant amplitude attenuation and the Nyquist-Shannon criterion should be fulfilled considering the filter's stopband.

- The CMM scanning speed or the rotary speed of the form measurement spindle/table should not be too high.
- The probing sphere should not be too large in diameter to avoid significant mechanical filtering of the surface. Even if a small enough probing sphere is selected, a distortion of the profile similar to the morphological operation of dilation will still occur.
- For open, non-periodic profiles, the length of the profile should match multiples of the waves to be measured. Otherwise FFT-based data analysis methods may fail. When the wavelengths are unknown it is difficult to fulfill this request.
- When the spectral analysis software can only treat data numbers that are multiples of 2 a further constraint exists for the number of data points. This request may be in conflict with b and/or f.

### SPECTRAL ANALYSIS OF MULTI WAVE STANDARD PROFILES

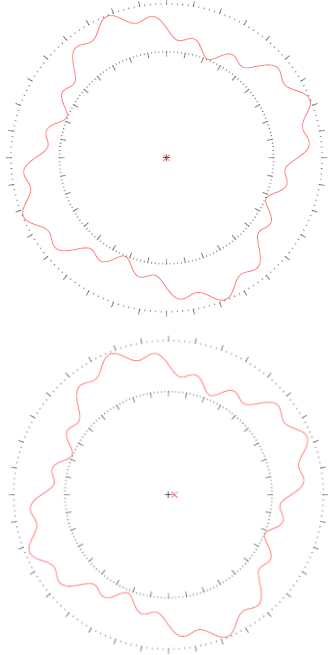
In dimensional metrology often spectral analysis of form profiles with assumed harmonic content is performed. In most cases it is assumed that the result of the application of a simple FFT algorithm to a profile results in a technically meaningful spectrum.

This section deals with several error influences to the resulting spectrum and their potential elimination.

#### Spindle or guide error influence

Guiding errors are a major influence to form deviation uncertainties. This is true both for rotary and linear axes of coordinate and form measurement instruments. The spectra of MWS profiles are nearly insensitive to guide errors. An example for a roundness profile can be seen in Figure 5, which shows a comparison of the simulation of an ideal and a distorted MWS form profile. The distortion was introduced to the profile by adding a sinusoidal half-wave as virtual guiding error. The form deviations  $RONt$  of the profiles differ by 8%. There is no influence to the heights of the dominant amplitudes, because the added guiding error only influences an amplitude at a lower frequency. Therefore, an efficient discrimination of wanted signal and external error source is possible.



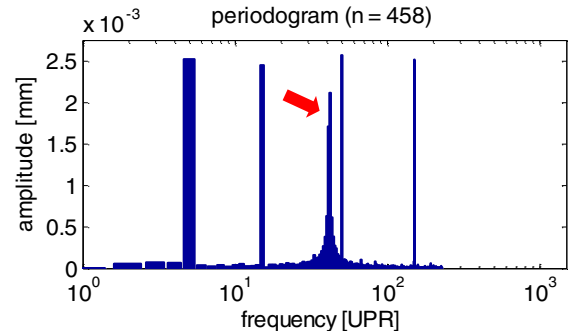


**FIGURE 5.** Comparison of simulated MWS form profiles (Arbitrary units) with (lower) and without (upper) an added small virtual guiding error. Although the form deviations differ significantly, the dominant amplitudes in the spectra do not.

#### **Aliasing and anti-aliasing filters**

Sampling is the reduction of a continuous signal to a discrete signal. If the continuous signal is bandwidth limited, the Nyquist-Shannon criterion [9, 10] defines a minimum limit to the sampling frequency, which should be equal or greater than twice the maximum frequency contained in the signal. When the sampling frequency is lower than the maximum frequency contained in the continuous signal, the discrete signal will suffer from a distortion called aliasing (subsampling frequencies appear as lower frequencies in the spectrum). Considering that continuous signals acquired from surfaces are usually not bandwidth limited (because of the wavelengths presented in the surface itself and/or because of the noise produced during the acquisition), also that there is a practical limit for the sampling interval which measurement systems can deliver, it becomes necessary to artificially limit the bandwidth of the signal in order to avoid aliasing. To provide a controlled bandwidth limitation, a hardware filter (known as anti-aliasing filter) should be incorporated to the signal transmission chain, before the discretization of the signal [11, 12]. Figure 4 shows the measurement of a MWS profile

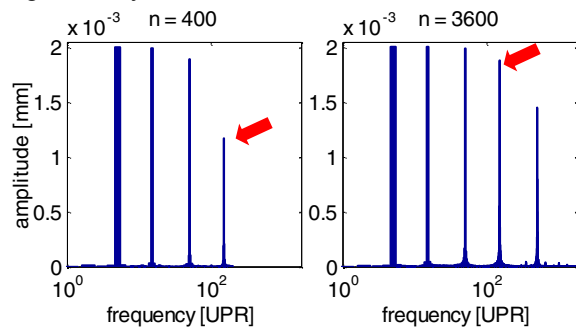
(circular track of the MWS from Figure 1) with a CMM. This measurement reveals that the used CMM does not have an anti-aliasing filter for the proper artificial bandwidth limiting of the profile according to the used number of points; consequently, the Nyquist criterion was not fulfilled, and the occurrence of aliasing is observed. It is important to note that if high frequency (or wide bandwidth) noise was generated during the acquisition of the profile, it would be integrally contained in the observed spectrum, severely disturbing the analysis.



**FIGURE 4.** Aliasing in the acquisition of a MWS profile (waves of 5, 15, 50, 150 & 500 UPR, nominal amplitudes of 2.5  $\mu$ m) acquired with a sampling frequency of 458 UPR by scanning with a CMM: The 500 UPR frequency appears below the 50 UPR frequency.

The transmission characteristic of the anti-aliasing filter is of extremely importance. The sampling frequency should be based both in how much aliasing can be accepted in the measurement (e.g. sampling frequency should be equal or greater than twice the filter's stopband); and in how much attenuation of the higher frequency of interest can accepted (which will depend on the inclination of the transmission characteristic, usually defined by the order of the filter) [12]. Figure 5 shows two measurements of a MWS profile (outer circular track of the MWS from Figure 2) with a form tester. Supposing that the 150 UPR was the higher frequency of interest, a sampling frequency of 400 UPR was selected (left). It can be noted that the anti-aliasing filter was capable of avoiding aliasing, but the frequency of 150 UPR was unacceptably attenuated. It can be concluded that, given the transmission characteristic of the anti-aliasing filter, the sampling frequency must be increased to a value fairly above the minimum sampling frequency (defined by the Nyquist criterion). For the second measurement (right), the sampling frequency was increased to 3600 UPR, and the

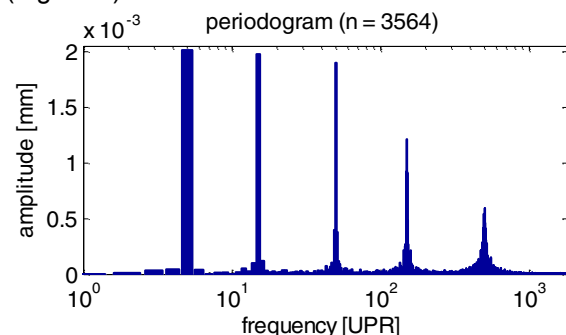
attenuation of the 150 UPR frequency was significantly reduced.



**FIGURE 5.** Attenuation of the 150 UPR frequency of a MWS profile (waves of 5, 15, 50, 150 & 500 UPR, nominal amplitudes of 2  $\mu\text{m}$ ) caused by the anti-aliasing filter (left) and the improvement after increasing the sampling frequency (right).

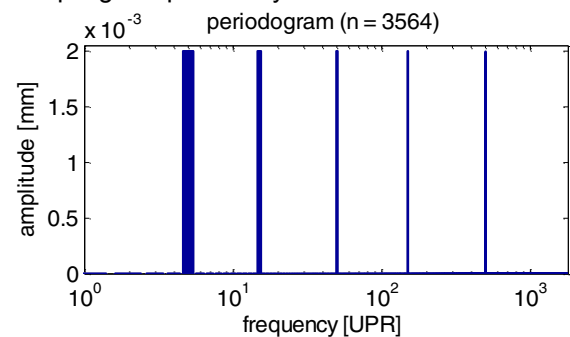
### **Non-even sampling**

Most scanning CMM sample by equidistant time triggering. Because the motion of the CMM axes may not be synchronous to time, especially when several axes are in motion and the acquisition is performed at high sampling rates, the spatial sampling becomes non-even. Similar but generally much smaller effects may occur during scanning by form measurement instruments. These devices generally trigger to the signal of angular encoders, if available. Although this would prevent the asynchronism problem of a CMM, imperfect angular encoders may introduce new errors. A direct consequence of the non-even sampling is the frequency spreading and amplitude attenuation observed on the spectral analysis via FFT algorithms which assume even spacing between points (Figure 6).



**FIGURE 6.** Effects on the spectral analysis of a simulated signal (360000 points, waves of 5, 15, 50, 150 & 500 UPR, nominal amplitudes of 2  $\mu\text{m}$ ) sampled with a angular distribution pattern emulating a CMM at a high sampling rate: Spreading and attenuation of the wavelengths.

If the real position of the points is known, the non-even sampled profile may be reconstructed by interpolation. A study of several methods of interpolation used in order to reconstruct non-even sampled profiles was carried out by Arenhart et. al. [13]. Among the evaluated methods, the cubic spline interpolation [14] showed to be the method which provided the best reconstruction for a given number of points (or, on the other way, the one who requires the least number of points per wavelength for generating similarly good results). Figure 7 shows the same signal of the Figure 6 after the interpolation using a cubic spline algorithm. It can be noted that the effects of non-even sampling are practically eliminated.



**FIGURE 7.** Spectrum of the reconstructed non-even sampled profile after the cubic spline interpolation.

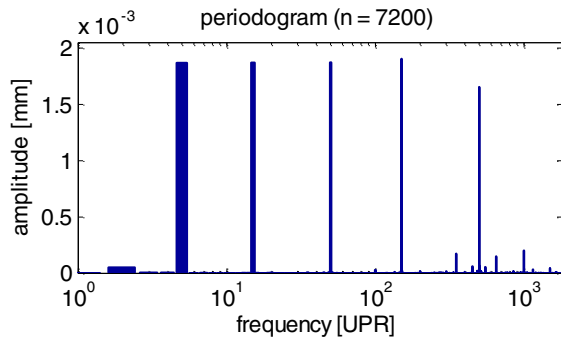
### **Mechanical convolution**

The acquisition of a profile from the surface of a work piece (e.g. a MWS) represents a mechanical convolution between the probing element and the local form deviations (e.g. the waves) of the surface. In the case of MWS, if the radius of a spherical probing element is too large to provide a continuous one-point contact with the surface, an effect known as mechanical filtering will occur, provoking loss of information about the sinusoidal components. The result of the mechanical filtering on the spectrum of a multi-sinusoidal profile is the attenuation of its amplitudes (especially for the smaller wavelengths) and the appearance of spurious wavelengths. Bosse [15] has calculated the maximum permitted sphere radius for a full one-point contact during the acquisition of a sinusoidal profile in order to avoid its mechanical filtering. The corresponding formulas lead to recommendations in standards [16, 17].

Even if a small enough probing sphere is selected and a two-point contact is avoided, the recorded points correspond to the center of the sphere, not to the actual contact points, so the

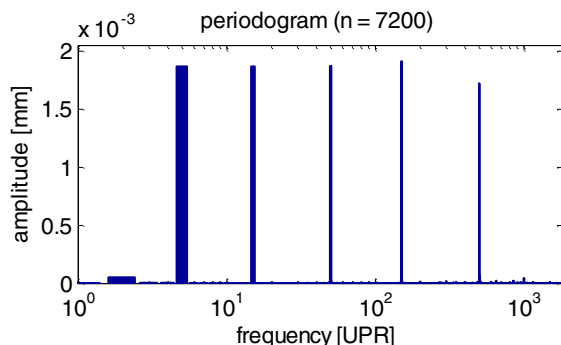
traced profile will still be a distorted representation of the real sinusoidal surface [11, 18]. This convolution is similar to the morphological filtering operation called dilation, and its occurrence will also lead to spurious points in the spectrum of the profile.

An example of this effect can be seen in Figure 8, which shows a spectrum of the inner profile of the MWS in Figure 2, acquired with a probing sphere having a 0.5 mm radius. The peaks near 500 UPR have no correspondence to waves on the MWS surface.



**FIGURE 8.** Effects on the spectral analysis of a MWS profile (waves of 5, 15, 50, 150 & 500 UPR, nominal amplitudes of 2  $\mu\text{m}$ ) due to the mechanical convolution: Spurious peaks appear near the 500 UPR frequency.

However, the distortion provoked by the mechanical dilation may be corrected by mathematical means. The use of the dilation's inverse primary morphological filtering operation called erosion, performed with a structuring element with the same size of the probing sphere, can be used for the reconstruction of the mechanical profile [11, 18]. This reconstruction technique results in a profile which more closely approaches to the real surface, practically eliminating the effects of the mechanical dilation on the spectral analysis.



**FIGURE 9.** Spectrum of the MWS profile after the erosion operation.

Figure 9 shows the spectrum of the same profile of Figure 8 after the reconstruction using the erosion operation. One requirement for an effective reconstruction is that no significant mechanical filtering has occurred during the acquisition.

### **Noise influence**

However, Krystek [21] showed that already a small amount of noise may severely influence the result of the FFT. These effects are additional and lost peaks in the spectrum and amplitude attenuation. That work further showed that an increased spectral resolution may help to avoid the noise sensitivity. Spectral resolution can only be increased by increasing the profile length not by increasing the number of data points as is assumed frequently. However, the profile length generally is limited by the size of the MWS or by constraints of the measuring instrument.

### **Non $2^n$ FFT algorithms**

Many simple FFT algorithms can only deal with data numbers equal to  $2^n$  with  $n$  being a positive integer. These are barely suitable for MWS analysis. Therefore we used IDL [19], MATLAB [20] and custom software, which can deal with all numbers of data points.

### **Non FFT-based spectral analysis**

For the waviness analysis on open structures like at the IWA shown in Figure 3 the conditions for the application of FFT algorithms are not fulfilled [21]. Therefore a new method is used which is based on a waviness model and which still assumes a superposition of sine waves but does not necessarily presuppose the periodicity of the resulting trigonometric sum. The model parameters "amplitude" and "wavelength" of each individual sine wave are determined by means of a novel algorithm which is based on Bayesian statistics. This procedure is based on the work of Rogazewski [22].

### **MEASUREMENT UNCERTAINTY**

In the Physikalisch-Technische Bundesanstalt (PTB) roundness MWS calibrations are performed regularly. Depending on the requirements of the geometry of the MWS and the required measurement uncertainty different measurement procedures using different kinds of form measurement instruments are chosen. Generally, reproducibilities of amplitude heights of the lower frequencies ( $\leq 150$  UPR) in the range of 1 nm can be achieved. Frequencies of

500 UPR and higher are more sensible to the described effects. Therefore the limiting factor to the measurement uncertainty is the absolute calibration of the probe sensitivity. We estimate that it can be performed with a relative standard uncertainty of approx. 0.25%. Therefore expanded measurement uncertainties of approx. 50 nm for the amplitude heights of typical MWS (i.e. with amplitudes in the range of 1  $\mu\text{m}$ ) are realizable. Note, that the uncertainties for the wave frequencies or wave numbers are zero, although they are not explicitly calibrated. If the wavelength of the MWS and the sampling interval matches, the spectral analysis algorithm will just result in an exact integer number for the frequency of the dominant amplitudes. For roundness measurements there is no sampling interval length issue, because the profiles are closed.

## CONCLUSIONS

MWS have become an indispensable tool for analyzing the signal transmission chain of CMM and form measurement instruments. However, the interpretation of raw measurement profiles requires a deep understanding of the influence parameters of the measurement process. Interpolation, morphological filtering, and advanced spectral analysis techniques may help to eliminate systematic errors and improve the measurement uncertainty. The topic is still under development.

## REFERENCES

- [1] ISO/TS 12181, Geometrical Product Specifications (GPS) – Roundness.
- [2] ISO/TS 12180, Geometrical Product Specifications (GPS) – Cylindricity.
- [3] ISO/TS 12780, Geometrical Product Specifications (GPS) – Straightness.
- [4] ISO/TS 12781, Geometrical Product Specifications (GPS) – Flatness.
- [5] Jusko O., Lüdicke F., Novel multi wave standards for the calibration of form measuring instruments. Proc. 1st EUSPEN, Bremen, Vol. 2, ISBN-3-8265-6085—X, 1999, 299-302.
- [6] Jusko O., Lüdicke F., Wäldele F., High Precision Form Measurements with Coordinate Measurement Machines. Proc. X Int. Surface Colloquium, Chemnitz, 2000, 341-351.
- [7] Härtig F., Krystek M., Klein S., Reliable detection of periodic micro structures on open surfaces. Proc. 8<sup>th</sup> Int. Symposium on Measurement Technology and Intelligent Instruments (ISMTII), 2007; Key Engineering Materials: 381/382 (2008) 15-18.
- [8] Härtig F., Jusko O., Richter O., „Evolventischer Prüfkörper mit überlagerten periodischen Strukturen (Wellen) zur Beurteilung von Messgeräten und Werkzeugmaschinen. DE 10 2005 042 278.
- [9] Nyquist H., Certain topics in telegraph transmission theory, Prox. Roy. Soc. Edinburgh, 35, (1915) 181-194.
- [10] Shannon C.E., Communications in the presence of noise. Proc. IRE 37, (1949), 10-21.
- [11] ISO/DTS 14406:2003, Geometrical Product Specifications (GPS) – Extraction.
- [12] Ifeachor E., Jervis B.W., Digital Signal Processing. Pearson Education Limited, Essex, England, 2002.
- [13] Arenhart F.A., Donatelli G.D., Porath M.C., Minimization of the uneven sampling effects on evaluating roundness with coordinate measuring machines. Proc. XIX IMEKO World Congress, Lisbon, 2009.
- [14] de Boor C., A Practical Guide to Splines. Springer-Verlag, 1978.
- [15] Bosse H., Aspekte der Filterung in der Formmesstechnik. PTB Bericht PTB-F-13, 1994, ISBN 3-89429-452-3.
- [16] VDI/VDE 2617 Part 2.2, Accuracy of coordinate measuring machines – Parameters and their reverification – Form measurement, 2000.
- [17] VDI/VDE 2631 Part 2, Form Measurement – Determination of the sensitivity of the signal transmission chain, 2001.
- [18] Gröger S., Dietzsch M., Gerlach M., Jeß S., “Real mechanical profile” – the new approach for nanomeasurements. Proc. 7<sup>th</sup> International Symposium on Measurement Technology and Intelligent Instruments (ISMTII), 2005; Journal of Physics: Conference Series 13 (2005) 13–19.
- [19] IDL, Interactive Data Language, <http://www.itvis.com/>.
- [20] MATLAB, <http://www.mathworks.de/>.
- [21] Krystek M., Kritische Betrachtung zum Einsatz der FFT in der Welligkeitsanalyse. PTB-Mitteilungen: 116 (2006), 3, 282-287.
- [22] Rogazewski P., Zur Approximation von Messwertfolgen mit nichtorthogonalen trigonometrischen Funktionen. Metrologische Abhandlungen. Berlin 9 (1989) 2, 125-136.



# THE IMPORTANCE OF SPINDLE BALANCING FOR THE MACHINING OF FREEFORM OPTICS

B. Knapp<sup>1</sup>, D. Arneson<sup>1</sup>, D. Oss<sup>1</sup>, M. Liebers<sup>1</sup>, R. Vallance<sup>2</sup>, E. Marsh<sup>3</sup>

<sup>1</sup>Professional Instruments Company  
Hopkins, Minnesota, USA

<sup>2</sup>The George Washington University  
Washington, District of Columbia, USA  
and Nano Precision Products Inc.  
El Segundo, CA, USA

<sup>3</sup>The Pennsylvania State University  
University Park, Pennsylvania, USA

## ABSTRACT

The topic of spindle balancing is a mature subject with modern two-plane balancing techniques attributed to Thearle's work from 1934 [1]. Despite exhaustive documentation in the literature, balancing and its effect on error motion measurement remains a misunderstood issue. In particular, the effect of unbalance on axial error motion is underappreciated. Unbalance-induced error motion is of critical importance for milling optics with high speed spindles. This paper demonstrates the effect of residual unbalance force on radial and axial motion of a 50,000 RPM air bearing micro-milling spindle.



FIGURE 1. Example of micro-milling an aspheric lens array with a high speed air bearing spindle. It is necessary to minimize fundamental axial structural motion in this application. Photo credit: Moore Nanotechnology Systems.

## INTRODUCTION

Unbalance at high speeds is a major concern in the manufacture of optical-quality freeform surfaces. It is well-documented that unbalance has little or no effect on surface finish in single-point diamond turning [2]. However, it has been shown that first and higher order harmonics can be excited in a machine structure by a rotating unbalance leading to features that are not concentric, flat or round [3]. Balance of rotational axes is critical in deterministic micro-cutting processes such as micro-grinding, raster fly-cutting, and diamond micro-milling (Figure 1). Vibration of a machine structure resulting from a rotating unbalance force or moment may lead to many problems, including fundamental (once-per-revolution) axial motion, higher order harmonic motion, inefficient or excessive tool loading leading to accelerated tool wear, and poor dimensional control with changes in speed.



FIGURE 2. Professional Instruments Company Model ISO 50K air bearing spindle.

## APPROACH

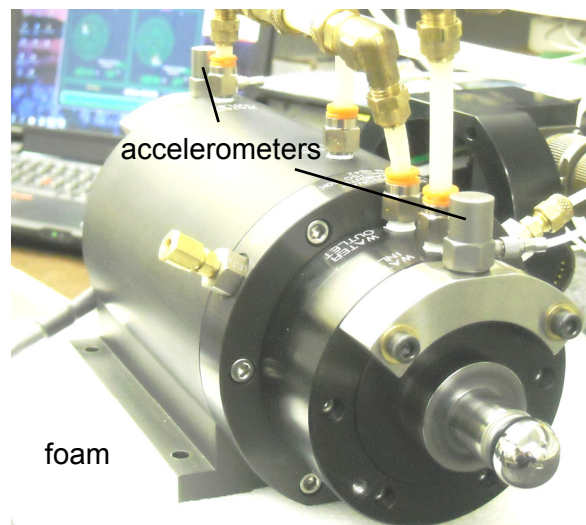
The spindle for this work (Professional Instruments Model ISO 50K) features integrated water-cooling, a 100-line count rotary encoder and a brushless, frameless motor and amplifier



(MCS motor and MCS AX-1000 amplifier). Correction is accomplished by adjusting the weight of M3 set screws in the front and rear of the spindle.

### **Balancing Setup**

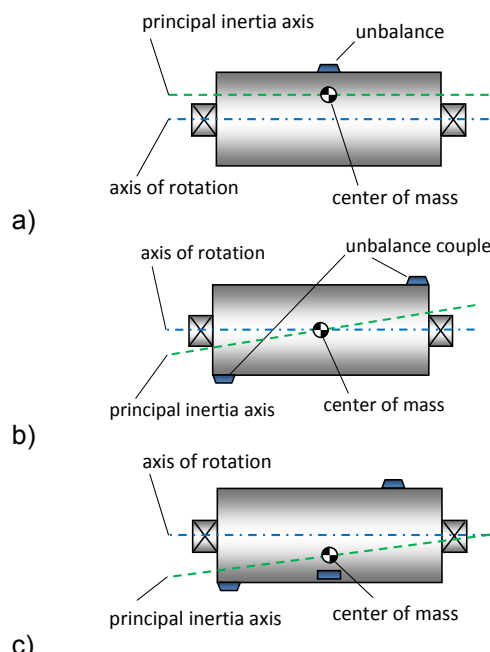
The setup for balancing the spindle on soft foam (2 pound extruded polyethylene) is shown in Figure 3. Accelerometers (Kistler K-shear 25 g) are mounted as close as possible to the two spindle correction planes. Screws of known weight are used to calibrate the output of the accelerometers. The spindle encoder is used for angular orientation and balancing software (Benstone Instruments Rotolab) calculates the required mass correction. Use of the encoder index eliminates the need for an external fiducial, such as reflective tape, which can negatively influence balance. Weight corrections on the order of micrograms are removed from M3 setscrews at each balance plane. This correction is so small that a buffing wheel is all that is needed.



**FIGURE 3.** The residual unbalance is measured with the spindle on foam. Accelerometers are located at the balance planes.

According to the international standard ISO 1925, there are four different types of unbalance: static, couple, quasi-static and dynamic [4]. As shown in Figure 4a), a static unbalance exists when the principal inertia axis is offset parallel to the axis of rotation. Although it is often used for spindle balancing, static balancing, or single-plane balancing, is appropriate only for narrow, disc-shaped parts such as flywheels [5]. Couple unbalance is illustrated in Figure 4b). Correction of the couple

unbalance requires two masses to create a correction couple.



**FIGURE 4.** a) Static unbalance, b) Couple unbalance, and c) dynamic unbalance after Stadelbauer [5].

Combined static and couple unbalance, or dynamic unbalance shown in Figure 4c), can be corrected using our procedure. Dynamic balancing using two balance planes is the only way to correct both the static and couple components of unbalance. For example, balancing the spindle in Figure 3 in only the front plane will likely cause increased unbalance in the rear plane and fundamental axial motion.

### **Error Motion Measurement Setup**

The ultra-precision air bearing in this work is designed to run up to 50,000 RPM with less than 25 nm axial and radial error motions. Accuracy requirements of this spindle demand rigid test hardware and minimization of external influences.

Error motion tooling shown in Figure 5 features a large granite base with passive air isolation, stiff steel structure with integrated constrained-layer damping and rigid sensor mounts. A capacitive sensor (Lion Precision C23-C, 2 V/ $\mu\text{m}$ ) targets a lapped spherical artifact in the radial and axial directions. The sensor amplifier (Lion Precision CPL290) incorporates a 15 kHz first-order, low-pass analog filter with linear phase response. The data acquisition system

(Lion Precision SEA V8.5) is triggered by the 100-line count encoder data channel, providing immunity to synchronization errors caused by speed variation.

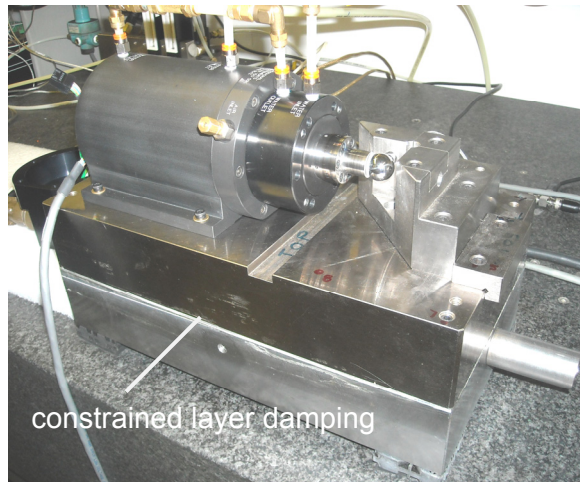


FIGURE 5. Tooling for radial and axial error motion measurement is designed to minimize structural error motion.

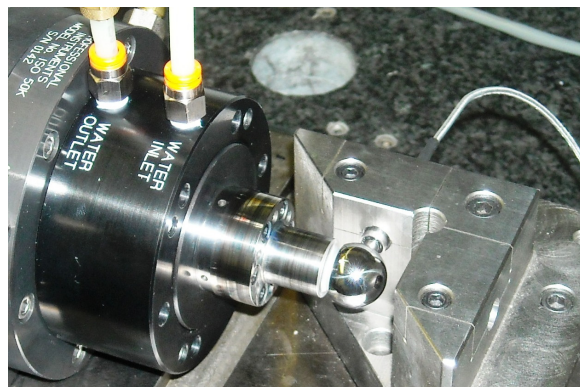


FIGURE 6. Close-up showing capacitive sensor and artifact for axial and radial error motion measurements.

Artifact shown in Figure 7 is a monolithic  $\varnothing 19$  mm flange-mounted ball for maximum stiffness and uniform circular compliance. The 5 nm out-of-roundness form error of the ball is not removed from test results. Elements of the structural loop from sensor to artifact are designed to be as stiff as possible. It is likely that an actual machine would have lower structural loop stiffness.



FIGURE 7. Monolithic  $\varnothing 19$  mm flange-mounted ball. The superior stiffness of the screw joint flange-mount and single-piece ball is essential for nanometer-level error motion measurement at high speeds.

## RESULTS

To demonstrate the importance of balancing and its effect on nanometer-level error motion, two sets of tests were performed. First, the spindle was balanced to ISO 1940 grade G2.5 and the radial and axial error motions were recorded. Then the balance was improved and the error motions were measured again.

### Balanced at ISO grade G2.5

The first set of tests simulates balance quality good enough for most machining applications. The magnitude of the rotating unbalance force is calculated for the front and rear balance planes. Residual unbalance is less than the allowable force for ISO 1940 grade G2.5 at all speeds as shown in Figure 6 [6].

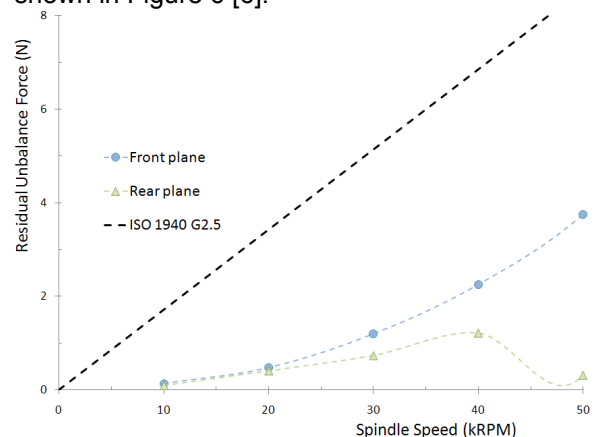
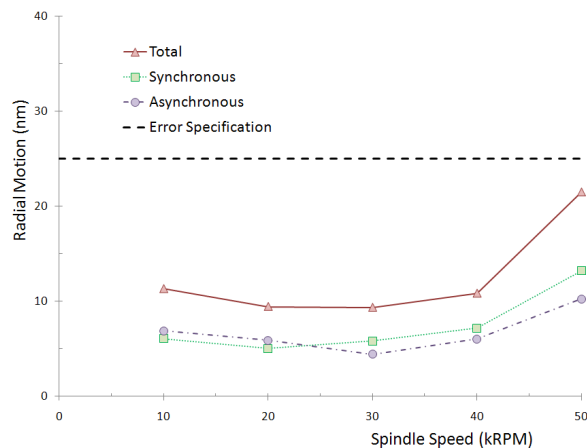


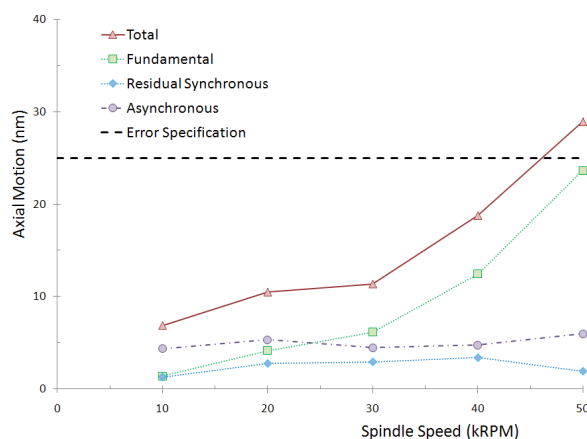
FIGURE 8. Spindle is balanced in both front and rear planes better than ISO G2.5.

Note that magnitude of the rotating unbalance force is shown here, as opposed to the standard units of unbalance (i.e., g•mm or oz•in). Quantifying the unbalance force can be more intuitive and tends to emphasize the effect of the unbalance on the spindle and structural loop.



**FIGURE 9.** Total radial motion including the artifact is less than 25 nm at all speeds with G2.5 balance.

The radial motion shown in Figure 9 includes spindle error motion, structural error motion and artifact out-of-roundness. The total radial motion is divided into synchronous and asynchronous components [2]. The results demonstrate less than 25 nm total radial motion over the operating speed range.



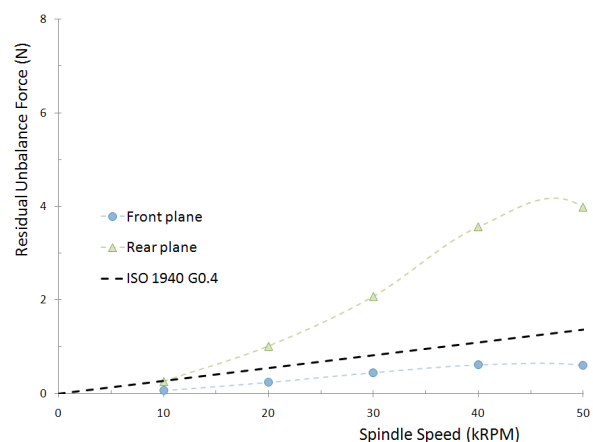
**FIGURE 10.** Total axial motion is less than 25 nm up to 40,000 RPM with G2.5 balance. The fundamental axial motion seems to track with the front plane unbalance as expected.

Axial motion shown in Figure 10 includes spindle error motion, structural error motion and artifact form and misalignment errors. The total axial motion is divided into fundamental, residual

synchronous and asynchronous components [2]. The results in Figure 10 demonstrate less than 25 nm total axial motion up to 40,000 RPM. The error motion at 50,000 RPM exceeds the specification and most of the error is presumed to be structural motion even though the tooling is robust.

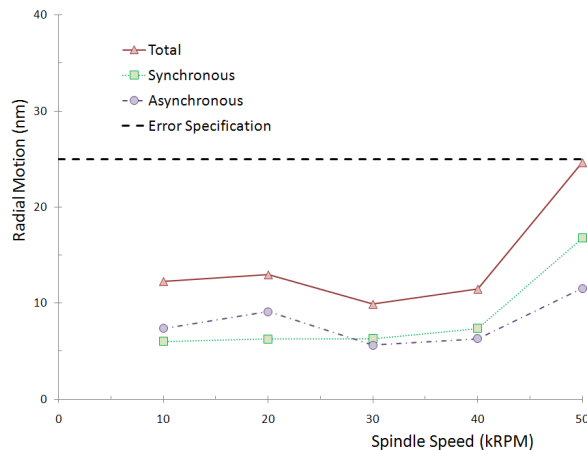
### **Front Plane Balanced at ISO grade G0.4**

The second set of tests simulates a more stringent balance requirement. With some effort, it is possible to reduce the unbalance level of the front plane to an ISO grade G0.4 as shown in Figure 11. The rear unbalance level is not as good as the front, but its effect on fundamental axial motion seems to be less significant.

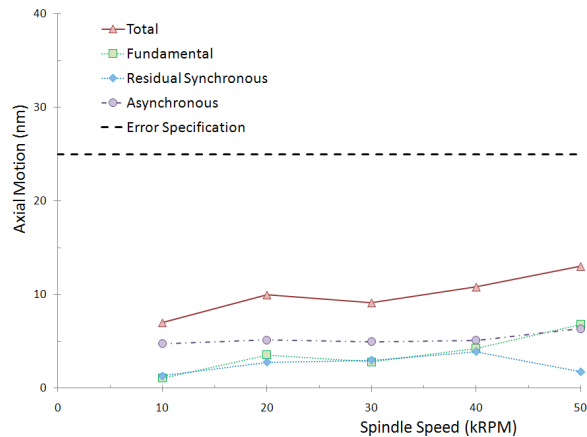


**FIGURE 11.** Spindle is balanced in front plane better than ISO grade G0.4. The rear plane is balanced as good as possible (ISO grade G1.0).

Radial motion measurement over the speed range with improved balance is shown in Figure 12. Total radial motion is nearly the same as before, due in part, to the fact that the test structure is so stiff. However, there is a slight increase in the radial motion at speeds above 40,000 RPM. This could be an indication of a transition from a rigid rotor to a flexible one [7].



**FIGURE 12.** Radial motion with improved balance. Total radial motion including the artifact is less than 25 nm at all speeds.



**FIGURE 13.** Total axial motion is less than 25 nm at all speeds with improved balance.

## CONCLUSION

Spindle balance is of critical importance in deterministic micro-cutting processes. It is particularly important in applications requiring surface form and finish on the nanometer-level.

As demonstrated here, fundamental axial structural motion can be reduced significantly through precision balancing. High resolution balancing is achieved using sensitive accelerometers and balancing on soft foam. A typical installation will likely have more structural compliance than the rigid error motion testbed used in this work. Therefore, the benefits of precision balancing in an actual machine tool will be even more dramatic.

## REFERENCES

- [1] E. L. Thearle, Dynamic balancing of rotating machinery in the field. Trans. American Society of Mechanical Engineers, J. Applied Mechanics. 1934; 56: 745-753.
- [2] ANSI/ASME B89.3.4. Axes of Rotation; Methods for Specifying and Testing. ASME, 2010.
- [3] Byran, J., Clouser, R., and E. Holland, Spindle Accuracy. American Machinist. December 4, 1967; pp. 149-162.
- [4] ISO 1925:2001. Mechanical Vibration – Balancing – Vocabulary. ISO. 2001.
- [5] Stadelbauer D. Fundamentals of Balancing. 2<sup>nd</sup> Edition. Schenck Trebel Corporation. Deer Park, New York: 1983.
- [6] ISO 1940-1:2003. Mechanical Vibration – Balance Quality Requirements for Rotors in a Constant (Rigid) State -- Part 1: Specification and Verification of Balance Tolerances. ISO. 2003.
- [7] Aspects of Flexible Rotor Balancing. 3<sup>rd</sup> Edition. Schenck Trebel Corporation. Deer Park, New York: 1980.



# MICROGRINDING WITH MICROWHEELS SHAPED BY MICRO ELECTRO-DISCHARGE MACHINING

Christopher J. Morgan<sup>1</sup>, Justin Huber<sup>1</sup>, and Scott Stephens<sup>2</sup>

<sup>1</sup>AMT nano, LLC

Lexington, Kentucky

<sup>2</sup>Department of Mechanical Engineering

University of Kentucky

Lexington, Kentucky

## INTRODUCTION

Freeform machining of hard materials is an important step in the fabrication of precision tooling. Precision tooling fabricated from materials like tungsten carbide can be used to replicate precision structures in difficult-to-machine materials like glass. The applications of this process are broad and include optics, biomedical sensors, and aerospace components. The two most common tooling materials are tungsten carbide and silicon carbide. These materials are preferred due to their high hardness and melting temperature; however, they are difficult to machine because mechanical cutting or shearing of the material results in unpredictable. Therefore precision, freeform machining of tungsten carbide and silicon carbide requires a grinding or polishing process. These approaches are not without complication though. Due to high wheel wear, suitable form accuracy and surface finish are difficult to achieve during freeform machining.

Typically, the grinding wheels are constructed of polycrystalline diamond (PCD) [1]. Several methods exist for producing PCD grinding wheels. Chemical vapor deposition (CVD) has been utilized to deposit diamond grains on the surface of tungsten carbide shafts. CVD-Diamond Pencils 100  $\mu\text{m}$  in diameter have been used to grind grooves in hardened steel. Wheels made entirely of PCD have emerged as suitable tools for microgrinding [2]. The PCD grinding wheels consist of sub-micrometer diamond grains sintered with metallic cobalt and shaped with micro electro-discharge machining ( $\mu\text{EDM}$ ) [3]. After shaping, the surface of a PCD wheel contains protruding diamond grains that are randomly distributed. When the wheel is rotated, the sharp protrusions act as hard and tough cutting edges for precision grinding. Solid PCD serves as a desirable platform for grinding

wheels because intricate shapes can be achieved by  $\mu\text{EDM}$ , and the wheel can be re-trued without wearing away the thin CVD layer of PCD. Moreover, by truing the wheel on the grinding spindle, any misalignment normally associated with tool transfer is avoided. Thus, subsequent grinding processes yield very low wheel wear. This paper discusses the application of these special grinding wheels and presents achieved freeform surfaces.

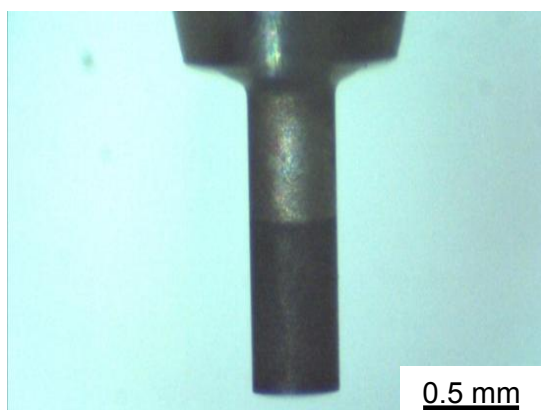
## GRINDING WHEEL FABRICATION

Micro electro-discharge machining ( $\mu\text{EDM}$ ) is a material removal process relying on discharges between a workpiece and a tool electrode that are connected by a relaxation (RC) circuit. The electrode and workpiece are submerged in a dielectric fluid and a potential is applied across the gap. Discharges occur when the electric field generated between the electrode and workpiece breaks down the interspersed dielectric fluid. This breakdown of the dielectric fluid is promoted by either reducing the distance separating the electrode and workpiece or by increasing the electric potential between the electrode and workpiece. Charging and discharging the capacitor in the RC circuit governs the potential difference and yields precise material removal. An electronic control system regulates the separation distance by monitoring the discharges. Energy from each discharge melts a small amount of material due to heating from the discharge plasma column. The molten material is flushed from the surface by the dielectric fluid when the plasma column collapses.

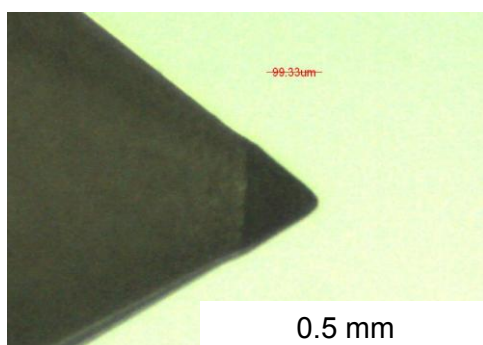
The PCD wheel blanks are shaped by rotating the wheel in a high precision spindle and discharging across a small gap to a sacrificial electrode. A variety of axisymmetric shapes can be realized by adjusting the position of the wheel blank relative to the electrode. Examples of



wheels fabricated with this process are shown in FIGURES 1 and 2. The transition from the substrate to the solid PCD is indicated by the transition from light to dark along the length of the wheel. The PCD grit size is 0.5  $\mu\text{m}$  or smaller and the binder material is cobalt. The wheels can be shaped with sharp, well-defined edges as shown in FIGURE 1, or with high sphericity as shown in FIGURE 2. To facilitate control and machining precision, the wheel stiffness can be maximized by shaping a conical geometry as shown in FIGURE 2. To manage debris, the grinding wheel can be surface engineered; by adjusting discharge energy during  $\mu\text{EDM}$ , the surface roughness can be modified to provide interstices for swarf collection.



**FIGURE 1.** Microscope image of a cylindrical, polycrystalline diamond grinding wheel.



**FIGURE 2.** Microscope image of an  $\text{Ø}36 \mu\text{m}$  spherical, polycrystalline diamond grinding wheel.

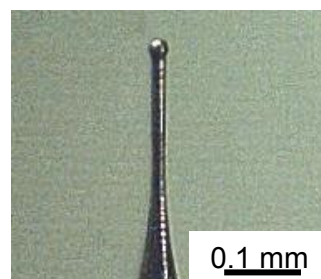
## GRINDING OF HARD MATERIALS

Minimizing wheel wear requires a trued wheel, which is typical for standard grinding processes.

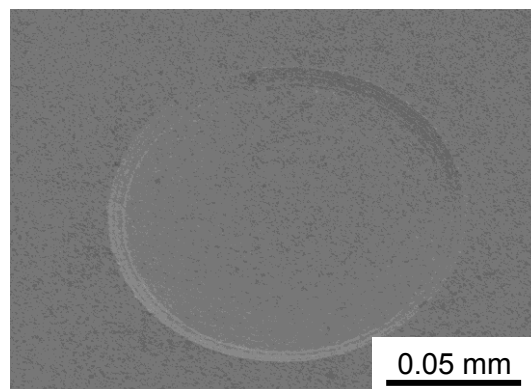
This consideration is addressed by a unique approach. After shaping with the  $\mu\text{EDM}$  process, the grinding wheels are not removed from the high precision spindle. Rather, the wheel shaping operation and the grinding process are performed on the same machine tool. First, the wheels are trued off-line at an auxiliary station. Next, the  $\mu\text{EDM}$  power supply is disconnected, and the grinding wheels are engaged with the workpiece. Several machine tool configurations have been utilized to shape a variety of structures in tungsten carbide. The results from each configuration are discussed below.

### Axi-symmetric Grinding

Grinding with a rotating wheel and rotating workpiece is common for standard OD and ID grinding. This configuration can be performed at the microscale shape precision cylinders, spheres, and optics. An example of a precision micro-probe ground in tungsten carbide is shown in FIGURE 3. FIGURE 4 is an image of a micro-optic ground in tungsten carbide with a spherical grinding wheel. The optic diameter is 75  $\mu\text{m}$  and the sag is 10  $\mu\text{m}$ .



**FIGURE 3.** Microscope image of a micro-probe ground in tungsten carbide with a cylindrical PCD grinding wheel.



**FIGURE 4.** Microscope image of a micro-optic ground in tungsten carbide.

## Freeform Grinding

At the micro-scale diamond grits on the PCD tool act as cutting edges. Therefore, the PCD tool mimics a milling tool and can be used for free-form machining. Consequently, intricate structures can be achieved by decomposing the desired microscale part into a sequence of tool trajectories. The cavity shown in FIGURE 5 features a deterministic geometry with straight sidewalls and continuous variations in depth. The cavity was achieved with a cylindrical grinding wheel approximately 20  $\mu\text{m}$  in diameter. Machine paths were programmed as if the grinding wheel was a micro-milling tool. Tool wear is extremely low as seen from the sharp edges at the bottom of the pocket. The engineered tungsten carbide surface in FIGURE 6 consists of a sinusoidal waveform with 4  $\mu\text{m}$  amplitude and two discrete wavelengths measuring 50  $\mu\text{m}$  and 150  $\mu\text{m}$ .

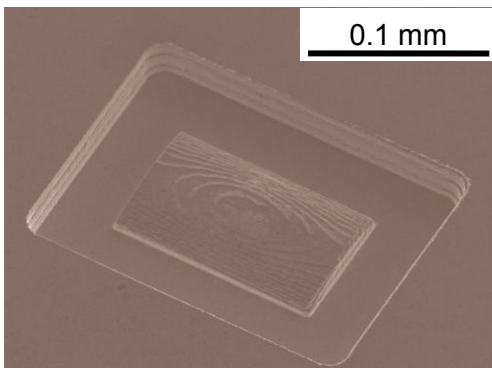


FIGURE 5. Microscope image of a micro-structure ground in tungsten carbide with a cylindrical PCD grinding wheel.

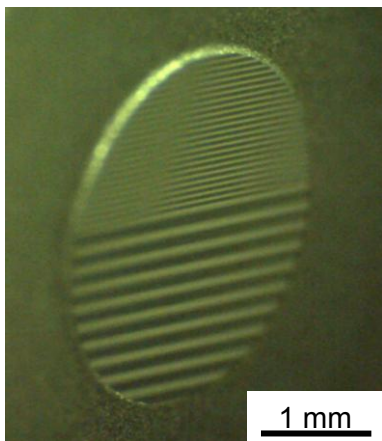


FIGURE 6. Microscope image of a micro-structure ground in tungsten carbide with the PCD grinding wheel shown in FIGURE 2.

## METROLOGY

The grinding operations facilitate highly precise machining, which can be verified using available metrology techniques. The three-dimensional control and precision afforded by the grinding process can be revealed by scanning white light interferometry (SWLI). A surface roughness of 25 nm RMS was measured on the bottom of the pocket by removing data from the surrounding areas.

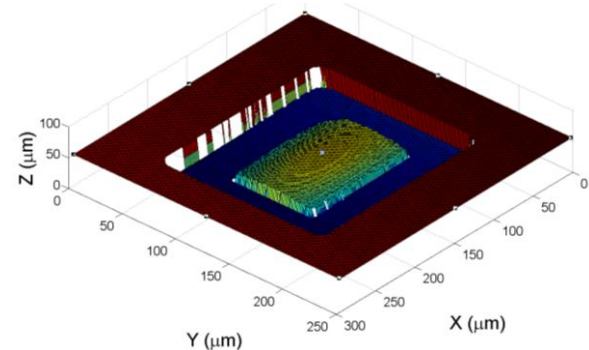


FIGURE 7. Three-dimensional structure machined by PCD tooling and measured by SWLI.

## CONCLUSIONS

Microgrinding offers unprecedented precision and accuracy at the microscale. By applying micro electro-discharge machining, grinding wheels can be shaped from solid polycrystalline diamond. The subsequent tool coupled with an ultraprecise, automated system permits machining of complex three-dimensional structures in hard materials such as tungsten carbide.

## REFERENCES

- [1] C. Morgan, "Microgrinding with Polycrystalline Diamond Microtools to Improve the Precision of Microscale Features," Doctoral Dissertation, University of Kentucky, 2008.
- [2] H. Hoffmeister, S. Illenseer, and J. Gäbler, "CVD-Diamantschleifstifte für den Werkzeug- und Formenbau Abrasive Pencils for Tool and Die Making Coated by Diamond CVD," *Vakuum in Forschung und Praxis*, vol. 16, no. 2, pp. 72-78, 2004.
- [3] Y. Liu, Y. Guo, and J. Liu, "Electric discharge milling of polycrystalline diamond," *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, vol. 211, no. 8, pp. 643-647, 1997.

# CHARACTERIZATION OF STRUCTURED SURFACES USING MULTI-PARAMETER BASED MASKING AND SEGMENTATION APPROACH

Suresh K Ramasamy, Brian D Boudreau, Jayaraman Raja  
Department of Mechanical Engineering & Engineering Science  
University of North Carolina at Charlotte

## 1. INTRODUCTION

In order to develop miniaturized products that deliver the same function at different scales, surfaces are being designed with different patterns at different scales. For micro-patterned optical surfaces, optical display characteristics are tested to qualify the surface. For surfaces that are designed to produce specific mechanical properties, like friction and wettability, actual surfaces need to be characterized. But, in many cases of patterned optical surface development, the geometry of the replicating dies surface can be characterized directly to ensure performance. These surfaces that are intentionally processed to possess a deterministic pattern or texture have been of particular interest from the surface characterization point of view, because regularly used height based and texture based segmentation techniques are not effective.

## 2. STRUCTURED SURFACES

A CIRP keynote paper [1] established the state of art for structured, textured or engineered surfaces. Stout and Blunt [2] refined the classification into:

- *Structured Engineered Surfaces* - surfaces with a deterministic pattern of usually high aspect ratio geometric features designed to give specific function. These surfaces are further classified into directional and non-directional surfaces depending on whether the surface exhibits directionality.
- *Unstructured Engineered Surfaces* - surfaces where the manufacturing process is optimized to generate variation in geometry and/or near surface material properties to give a specific function but without a deterministic pattern.

## 3. CHARACTERIZATION METHODS

Traditional surface characterization methods using statistical means are not useful for structured surfaces. For structured engineered surfaces, there is a need to identify the deterministic pattern, characterize manufacturing variations of the pattern, separate background surface from the patterns and segment individual facets forming the pattern before getting into surface analysis of the individual facets or shapes. Multi-scale analysis has been suggested as a possible way to perform the above mentioned pre-processing steps before analyzing individual facets or micro-arrays.

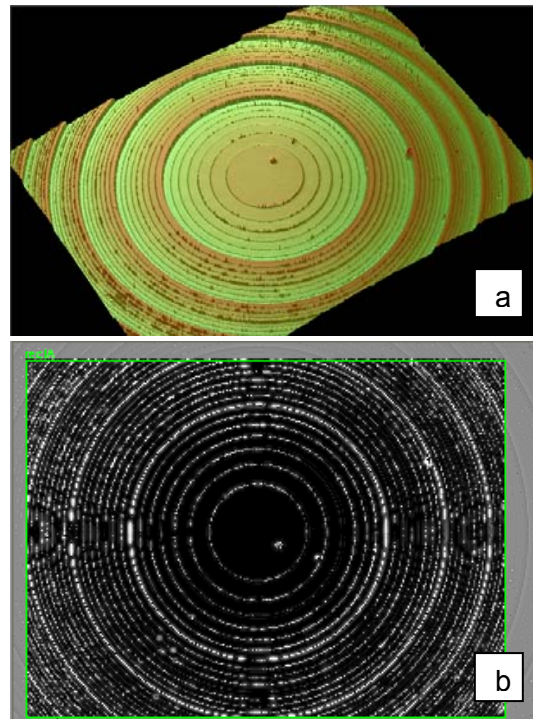


FIGURE 1: (a) 3D surface data of Fresnel lens (b) edge detection using Canny operator

Two major approaches [3] towards development of multi-scale analysis of surfaces are fractals and wavelets. Wavelets present advantages over traditional methods with their space-frequency localization and multi-scale analysis capabilities. Mathia et al [4] discuss about the need for an automated method to segment the structured surfaces into regions of interest. For patterned surfaces with stepped planar surfaces, like Fresnel micro-lens arrays, currently available height histogram based separation of surfaces [5] and edge detection in image analysis domain can be readily used as shown in figure 1.

#### 4. SEGMENTATION APPROACHES - STATE OF THE ART

Senin, Ziliotti and Groppetti [6] propose a clustering based segmentation. They have successfully applied the already developed methods in image analysis domain to segmentation of 3D surface data, under the premise that 3D surface data could also be treated similar to gray scale image data. They also mention that the only other image analysis based method deployed in surface topography domain – watershed based segmentation [7], which is being included in the new ISO standard [8] for areal surface texture characterization. Clustering based on one parameter, albeit on any transform domain is the main suggestion of the authors. When suggesting the use of multiple parameters, they took the weighted average approach to find one metric which is a weighted average of selected parameters. They conclude that multi-parameter method is not significantly better than one parameter method.

Verma and Raja [9] have developed a MATLAB® based software system to automatically locate features on the surface and dimensionally characterize them. Once the segmentation is performed, features are extracted and primary objects are identified and then dimensions are calculated. Kong et al [10] have presented an image processing approach to the characterization of optical microstructures, mainly on the spatial height based data separation approach.

#### 5. PROPOSED APPROACH

Using Hough Transform [11] and Radon Transform [12] to identify specific patterns on engineered surfaces has already been documented. The peaks on data obtained using either of the transforms are used to generate an image of interest, which could be further processed using standard image morphological analysis tools. Our approach takes a next step from the single parameter based segmentation approach and proposes the use of multiple parameters for segmentation. The concept is very much in use in the image analysis domain [13], where the image is converted to any other domain and two different parameters are analyzed in a 2D histogram to find individual clusters. The clusters can be identified and separated using regular thresholding algorithms and corresponding indices are used to separate the height data into multiple segments. The conceptual schematic is shown in figure 2.

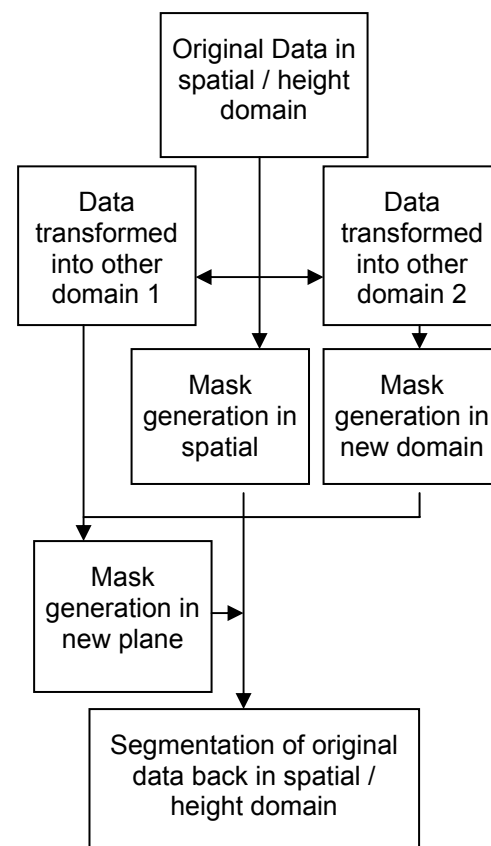


FIGURE 2: Schematic showing the multi-parameter based segmentation approach



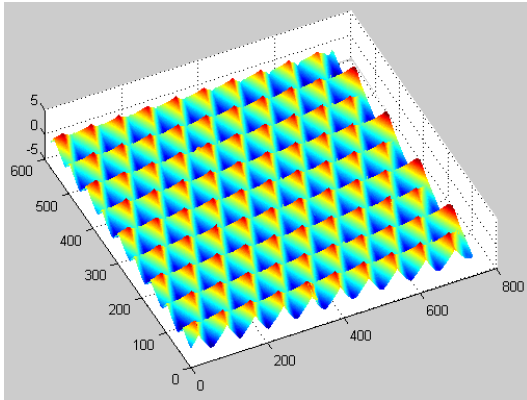


FIGURE 3: Pyramid patterned surface

## 6. CASE STUDY

As an example, a pyramid patterned surface is taken, as shown in figure 3. Each pyramid is made of three facets. The variation in pyramid pattern spacing and angles made by three facets need to be calculated which requires separating the entire surface into three segments containing only the individual facets for further surface analysis. As a first stage, it is shown that instead of generating masks in the height domain, mask can also be generated in different transform domains for segmentation purposes.

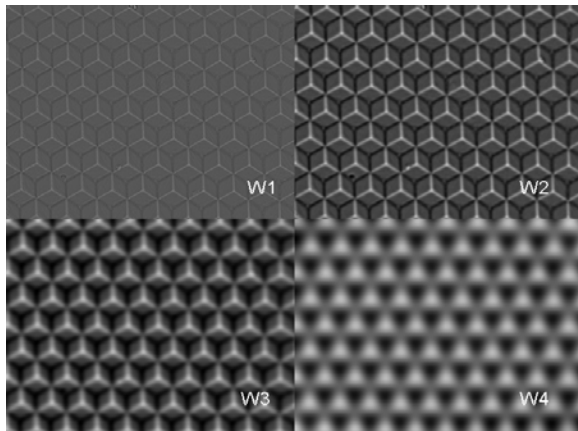


FIGURE 4: Images obtained by DWF Transform

In order to find the edges of the pyramid structure, a Discrete Wavelet Frame (DWF) Transform [14] is performed (B3 Spline, 4 levels) and the obtained wavelet planes are shown in figure 4. It can be seen that planes W1 and W2

could be used to find the edges, as shown in figure 5.

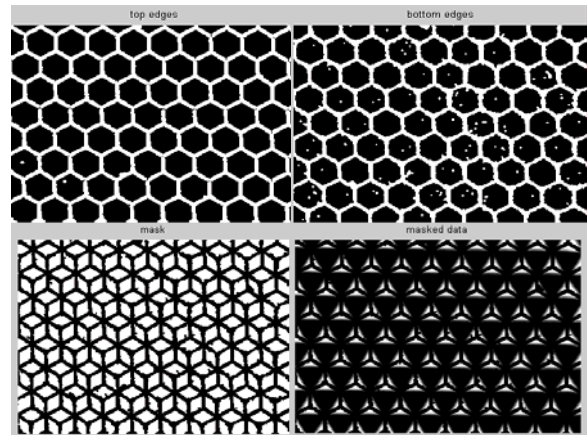


FIGURE 5: Edge detected on W1 Image obtained by DWF Transform

The 3D representation of the masked data is shown in figure 6. Even though the individual segments have been identified, the segments are not grouped into three different facets.

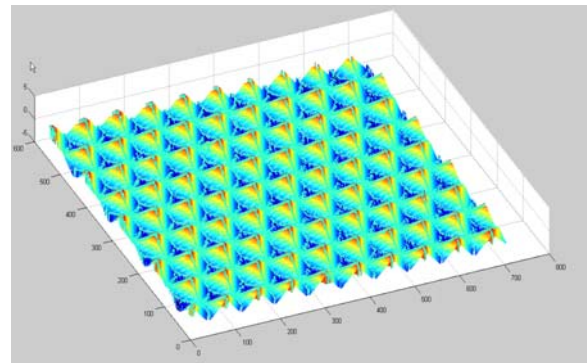


FIGURE 6: Segmented dataset obtained by applying the binary mask to original data

Having shown the possibility of using DWF transform for masking and segmentation of directional structured surface, we get into multi-parameter based masking and segmentation as the second stage.

The x and y gradients of the height data are calculated and a 2D histogram (with 200x200 bins) of the slopes is generated as shown in figure 7. Generic peak picking algorithms could be used to identify the number of peaks in the histogram and used to separate the cluster data



closed to these three peaks. Sub-images a – c in figure 8, show the segmented individual facets and figure 8d shows the combined image color coded to show the three facets of the pattern.

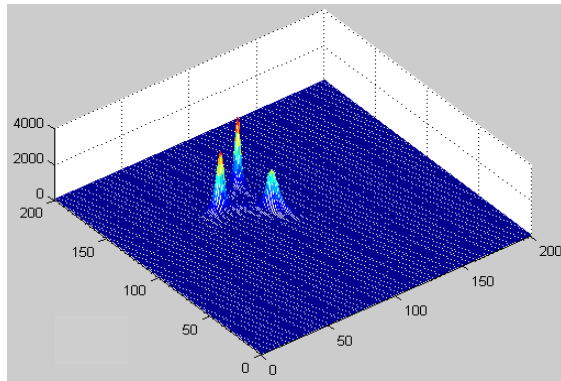


FIGURE 7: 2D histogram plot of slopes

Once the three facet data is grouped, each facet can be separated, segmented for further analysis.

This case study deals with two parameters, namely x and y slope gradients, but this concept could be readily applied to other surface parameters that naturally assume two or more

interrelated components (e.g. 3D surface slopes, normals, curvatures, etc) depending on the application.

## 7. SUMMARY

Structured surfaces pose a unique challenge in segmentation, analysis and characterization. The prevailing practices in digital image analysis techniques are adapted to be used for these special surfaces. The main contributions of this paper are:

- Apart from masking in height domain, it is demonstrated to perform masking in any other domain.
- Demonstrating that segmentation need not be limited to one parameter or a weighted average of multiple parameters, but rather 'n' parameters could be treated individually in  $n^{\text{th}}$  dimension domain using cluster analysis.

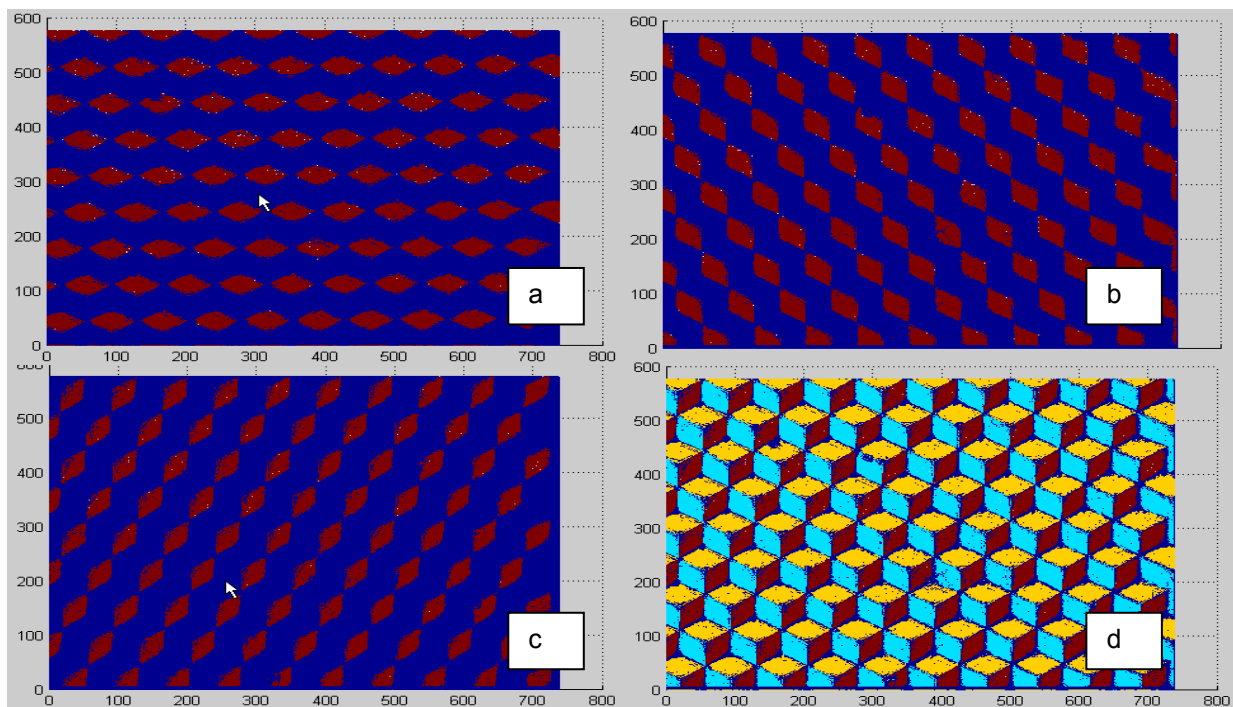


FIGURE 8: (a-c) three individual facets (d) all three datasets shown together

## REFERENCES:

- [1] C. J. Evans, J. B. Bryan, "Structured", "Textured" or "Engineered" surfaces, *Annals of CIRP*, Vol 48/2/1999, pp. 541-556.
- [2] K. J. Stout, L. Blunt, A contribution to the debate on surface classifications – random, systematic, unstructured, structured and engineered, *international Journal of Machine Tools & Manufacture* 41, 2001, pp. 2039-2044.
- [3] G. W. Stachowiak, P. Podsiadlo, Characterization and classification of wear particles and surfaces, *Wear* 249, 2001, pp. 194-200.
- [4] T. G. Mathia, P. Pawlus, M. Wieczorowski, Recent trends in surface metrology, *Wear* 2010 (Article in press)
- [5] S. Ramasamy, A. Kasper, Expanding white light interferometer capabilities to be used as a  $\mu$ -CMM, *Proc. of 25<sup>th</sup> ASPE Annual Meeting*.
- [6] N. Senin, M. Ziliotti, R. Groppetti, Three-dimensional surface topograph segmentation through clustering, *Wear* 262, 2007, pp. 395-410.
- [7] P. J. Scott, Pattern analysis and metrology: the extraction of stable features from observable measurements, *Proc. R. Soc. London A*, 2004, 460, pp 2845-2864.
- [8] ISO/TC 213 Draft N 755, Geometrical Product Specifications (GPS) – Surface Texture: Areal- Part 3: Specification Operators.
- [9] R. Verma and J. Raja, Characterization of engineered surfaces, *Journal of Physics: Conference Series* 13, 2005, pp. 5-8.
- [10] L.B. Kong, C.F. Cheung, X.Q. Jiang, W.B. Lee, S.To, L. Blunt, P. Scott, Characterization of surface generation of optical microstructures using a pattern and feature parametric analysis method, *Precision Engineering* 34(2010) pp 755-766.
- [11] Z. Dimkovski, C. Anderberg, B.-G. Rosen, R. Ohlsson, T.R. Thomas, Quantification of the cold worked material inside the deep honing grooves on cylinder liner surfaces and its effect on wear, *Wear* 267 (2009) pp 2235-2242.
- [12] B. Xin, Multiscale analysis of rough groove textures for three-dimensional optical measurements, *Optical Engineering* 48(7) 073602, July 2009.
- [13] J. C. Russ, *The Image Processing handbook* Ch 7: Segmentation and Thresholding, pp. 397-441, 5<sup>th</sup> edition, CRC Press.
- [14] X. Zhang, D. Li, À Trous wavelet decomposition applied to image edge detection, *Geographic Information Sciences*, Vol. 7, No. 2, 2001, pp.119 – 123.

# FIVE AXIS POLISHING OF FREEFORM PRECISION OPTICS

**Shai N. Shafrir; Edward Fess; Vince Cannarozzo;  
Scott T. Bambrick; Jayson Tierson  
OptiPro Systems, Ontario, NY 14519**

Freeform optics provide significant benefits for applications in the areas of LED lighting, compact projection television, heads up displays, and conformal optics sensors and windows (aerodynamic and hydrodynamic). However, optical designers are hesitant to use freeform optics in the design stage due to fabrication and metrology limitations. In this work we demonstrate a simplified motion control, programming effort, and specialty fixtures that were developed for polishing a complex optical element. This effort resulted in reduced set-up time and increased accuracy by limiting part reposition/blocking, and subsequently better figure control, and better surface finish. Computer aided manufacturing (CAM) software called Mastercam was used for “dry” simulation of tool motion across the part (i.e., tool path) to confirm consistent material removal rate over the surface. Actual polishing runs were successfully done for optical glasses as well as ceramics and metals.

Polishing tests were conducted using a commercial computer numerically controlled (CNC) machine platform called UltraForm Finishing (UFF). The UFF is a sub-aperture polishing machine that uses five axes of motion: three linear axes (x, y, and z) and two rotational (one controls the polishing head swing from -90° to 90° and the other controls the sample piece rotational positioning, corresponding to b and c axes, respectively). Material removal is done by a utilizing a continuous polishing belt supported by a polyurethane rotating wheel with nominal hardness ranging from soft to hard. This polishing belt can either be impregnated with polishing compounds or used in conjunction with traditional polishing slurries, which allowed us to adjust the polishing medium to the tested material. The length of the polishing tool, or “arm”, can be adjusted for polishing deep concave shaped optics (such as ogive missile domes), in addition the wheel diameter can be modified to account for the local radius of curvature of the freeform optic.

We studied the usefulness of non-rotationally mode polishing via the UFF and discuss the creation of a sample model. This approach overcomes the inherent limitations of polishing a rotationally symmetric part which occurs when the part and tool are both positioned on the same axis (z-axis in our case) resulting in undesirable material removal in one location. The technique was tested for a toroidal surface that was chosen as an example of freeform non-rotationally symmetric surfaces. The toroid has two different radii of curvature: approximately 100 and 160 mm, respectively. The non-rotational component or the sag difference between the two radii's was approximately 10 mm. We will discuss the considerations for the tool path configurations, as well as other machine parameters.

# DIRECT ENGRAVING OF 20- $\mu$ M WIDE PATTERNS INTO A NI-PLATED ROLL USING FIBER LASER

H. Sohn, J. Suh, J. K. Park

Nano Convergence & Manufacturing Systems Research Division

Korea Institute of Machinery & Materials

104 Sinseongno, Yuseong-gu, Daejeon, 305-343, Korea

## INSTRUCTIONS

For low-cost and mass production in printed electronics, electronic ink is transferred onto a flexible substrate using a printing roll. It generally is fabricated by the indirect laser engraving method in which a laser beam is scanned over a photoresist (PR) film pre-coated on a Cu plated roll in order to form an etch barrier for chemical wet etch of the Cu layer [1,2]. On the patterned Cu layer, chromium is thinly electroplated to finish the indirect printing roll engraving process.

Although well-established, the indirect laser engraving method is a multi-step process and even inherently includes the etch process which is environmentally unfriendly. Thus, many research efforts have been devoted to developing simpler and non-chemical laser engraving methods [3].

In this work, we have directly engraved micro-scale patterns into a Ni plated printing roll using a fiber laser. We also fabricated a prototype equipment for the direct laser engraving. Using the prototype, we conducted experiments to investigate the effects of the variables, laser power and revolution speed.

## Experimental

Figure 1 and 2 shows the experimental setup for the direct laser engraving. It mainly consists of a fiber laser for engraving patterns, a precision rotation motor for rotating a Zn electroplated cylinder and a precision one-axis linear stage for transferring an objective lens focusing laser beam onto the rotating cylinder.

TABLE 1. Specifications for the fiber laser used in experiments

| Wavelength (nm) | Average power (W) | M <sup>2</sup> | Pulse width (ns) | Repetition Rate (kHz) |
|-----------------|-------------------|----------------|------------------|-----------------------|
| 1064            | 12                | 1.5            | 34               | 20-80                 |

To engrave a Ni plated steel cylinder, we used a 12W pulse-modulated fiber laser (IPG photonics, USA). The specifications for the fiber laser are summarized in Table 1. Laser beam from the laser head is delivered using two bending mirrors and focused on the cylinder by an objective lens (Microspot, USA).

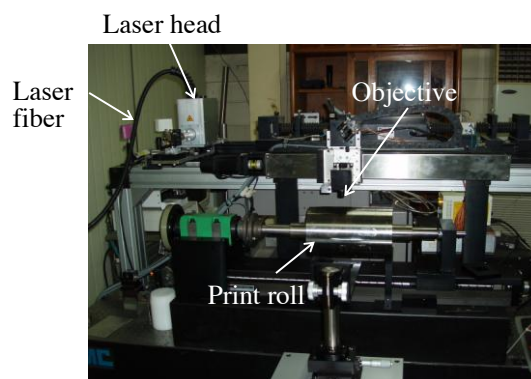


FIGURE 1. Experimental setup

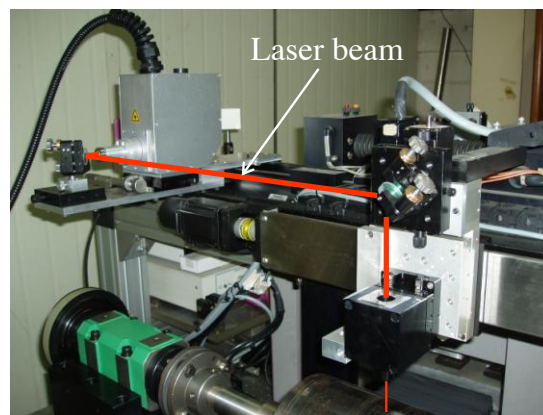


FIGURE 2. Laser beam delivery

One end of a cylinder is fixed using a dead center and a flange similarly in case of a lathe. The flange is indirectly connected to the rotation motor using a timing belt in order to decouple

the vibration from the motor as much as possible. The other end of the cylinder is fixed using a steel ball to minimize the deviation of the cylinder from the rotation center. To control the rotation of the cylinder, a rotational encoder with 131,072 counts per revolution is attached to the flange.

### Results and discussion

To prepare a Ni plated printing roll for laser engraving, first a steel roll is machined and polished. Then it is Cu plated and polished again. Finally, a about 80  $\mu\text{m}$  thick Ni layer is electroplated. The roll is 125 mm in diameter and 300mm in length. Due to the higher evaporation energy and thermal conductivity, the Cu layer acts as an ablation barrier while the printing roll is being engraved.

In experiments, the laser power and the revolution speed were set as the variables. Since the fiber laser used in the experiments is pulse-modulated, the heat energy from the laser is transferred in the form of succeeding pulses. The fluency of laser beam ( $\text{J}/\text{cm}^2$ ) to the roll surface is thus determined by the combination of the interval of succeeding pulses and the revolution speed of the roll. When set at 100%, the laser power is 12W.

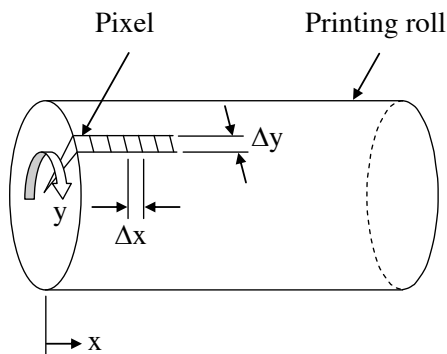


FIGURE 3. Input file mapping into a printing roll surface

The actual size of the designed patterns can be adjusted by mapping the input file to the printing roll surface (FIGURE 3.). The printing roll surface can conceptually be divided into a large number of pixels. The minimum pixel size along the x axis  $\Delta x$  depends on the resolution of the one-axis linear stage transferring an objective lens, i.e.,  $\Delta x$  equals to  $1\mu\text{m}$ . And the minimum pixel size along the y axis  $\Delta y$  depends both on

the resolution of the rotational encoder and the printing roll diameter. Since the rotational encoder is with 131,072 counts per revolution and the electroplated printing roll has a diameter of 125 mm,  $\Delta y$  equals to  $2.99\mu\text{m}$  (FIGURE 4.).

To map the input file to have a designed size on the printing roll surface,  $\Delta x$  and  $\Delta y$  should be calculated based on the ablated pit size on the printing roll surface at a certain combination of laser power and revolution speed. The fabricated prototype engraving equipment has a function of changing the value of  $\Delta x$  and  $\Delta y$  with ease.

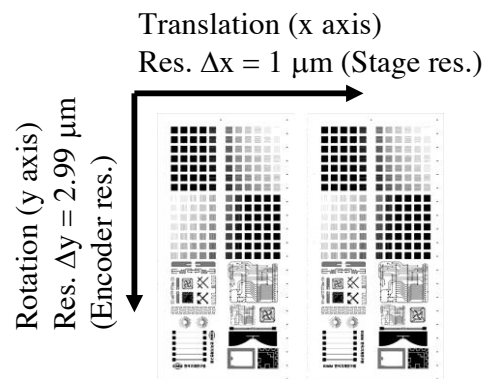


FIGURE 4. Resolutions in the x and y direction

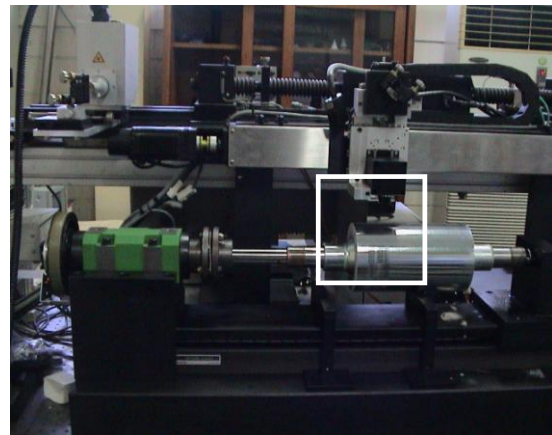


FIGURE 5. Laser direct patterning

### Summary

To address challenges that the conventional indirect laser engraving method based on the etch process, micro-scale patterns have been directly engraved into a Ni plated printing roll using a fiber laser. A prototype engraving equipment has also been fabricated. Based on



the experiment results, we have engraved various patterns on a Ni plated printing roll with a diameter of 125mm.

#### REFERENCES

- [1] B.Y. Ahn: *Printing Engineering*, Sejinsa, Korea 1997.
- [2] H.H. Xiao: Proc. SPIE Vol. 2118, 1994, p. 209-212
- [3] [www.daetwyler.com](http://www.daetwyler.com)

# AN EXPERIMENTAL STUDY ON REAL-TIME MONITORING OF GRINDING WHEEL SURFACE SHAPE AND TOPOGRAPHY WITH ULTRA-HIGH FREQUENCY LASER DISPLACEMENT SENSOR

Matthew R. Stanco<sup>1</sup>, Loren A. Bryant<sup>1</sup>, Jesse Vergara<sup>2</sup>, Z.C. Li<sup>1</sup>

<sup>1</sup>Department of Industrial and Systems Engineering  
North Carolina Agricultural and Technical State University  
Greensboro, NC, USA

<sup>2</sup>Keyence Corporation of America  
Charlotte, NC, USA

## ABSTRACT

An innovative measurement method to characterize the grinding wheel surface shape and topography is proposed and tested in the present paper. An ultra high-speed/high-accuracy laser displacement sensor is integrated with a data acquisition system to measure the grinding wheel surface shape and topography for the first time. The measurement method is further developed to calculate and track grinding ratio (i.e. G-ratio) in real-time.

## INTRODUCTION

The grinding process represents a crucial stage in the manufacture of many advanced engineering materials such as ceramics, semiconductors, and titanium alloys etc. Grinding allows the achievement of precision dimensions, tolerance, and surface finish, which are not attainable by other machining processes like drilling, milling, and turning [1]. The degree to which such specifications can be met is heavily influenced by the grinding wheel's surface shape and topography. In grinding, irregularities on wheel surface shape and topography due to the wheel wear can prove detrimental to the quality of subsequent workpieces. Therefore, the grinding wheel needs to be dressed to return the wheel to original shape and regenerate sharp topography.

The underlying purpose of the grinding process is to randomly remove microscopic chips [2]. This process causes weathering to occur on the actual grinding wheel, affecting the surface topography of the grinding wheel. This surface topography of the grinding wheel is derived from the distinct truing and dressing methods that are employed [3] as well as the grinding process itself. Due to its arbitrary nature, wheel topography cannot be accurately established [4].

In this study, an innovative measurement method to characterize the grinding wheel surface shape and topography is proposed and tested. An ultra high-speed/high-accuracy CCD laser displacement sensor is integrated with a data acquisition (DAQ) system to measure the grinding wheel surface shape and topography for the first time. In addition to characterizing the wheel surface shape and topography, the proposed measurement method also can be used to track differences in mean distance to wheel surface (i.e. changes in the wheel's radius). The change in grinding wheel radius can be used to calculate the change in grinding wheel volume. Therefore, the proposed measurement method also helps to track grinding ratio (G-ratio) for any particular grinding process and grinding wheel with unprecedented precision.

## EXPERIMENTAL DETAIL

### Laser Displacement Sensor

The laser displacement sensor in this study consists of a laser diode, several optical lenses, and a light sensitive detector. The laser diode projects a beam of light onto the grinding wheel surface. Some of the light is reflected off the surface onto the detector through a receiver lens. Then the detector records the position of the reflected laser beam and reports a height measurement. As the grinding wheel rotates, the wheel surface changes its position with respect to the detector. The movement of the reflected light is projected on the detector array and recorded to output the exact position of the target surface. Data of the recorded positions are processed digitally in the integral controller and converted into a scaled output via analogue (I/U) and digital interfaces such as USB. The main advantage of laser distance sensor is that the laser light has a much smaller wavelength, allowing one to send out a much more

concentrated probe beam and thus to achieve a higher transverse spatial resolution, long measuring ranges, performance independence from target material and higher reference distance. Another advantage that an optical bandpass filter makes it possible to very effectively remove noise influences at other optical frequencies.

### Experimental Setup

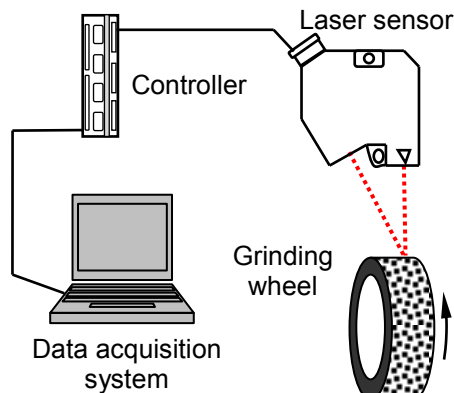


FIGURE 1. Schematic Illustration of Experimental Setup.

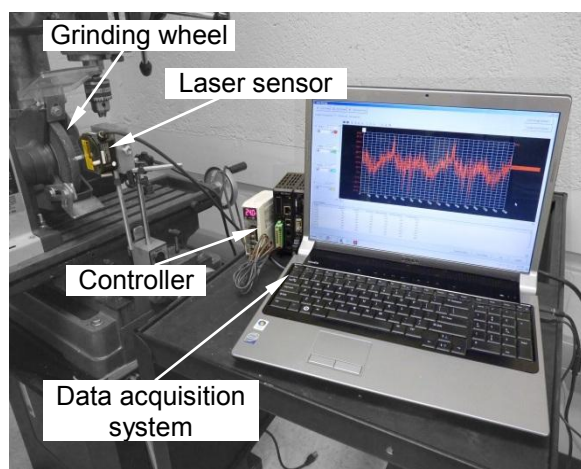


FIGURE 2. Photograph of experimental setup.

A schematic depiction and a photograph of the experimental setup are illustrated in FIGURE 1 and FIGURE 2, respectively. It consists of a rotating grinding wheel, a laser measurement system (including the CCD laser displacement sensor and the controller), and a data acquisition system.

The laser displacement sensor utilized is the LK-H057 (Keyence Corporation, Osaka, Japan). A 24VDC power supply drives the laser controller

LK-G5001. A laptop computer interfaces with the laser controller via a USB connection and provides a means of laser control as well as data recording and analysis by the LK-Navigator 2 software (Keyence Corporation, Osaka, Japan). Other detailed specifications of the sensor are enumerated in Table 1 below.

TABLE 1. Specifications of the laser sensor

| Specifications             | Value                                    |
|----------------------------|------------------------------------------|
| Reference distance         | 50 mm                                    |
| Measuring range            | $\pm 10$ mm                              |
| Light Source (wavelength)  | 690 nm                                   |
| Light Source (laser class) | IEC60825-1 Class 3B                      |
| Light Source (output)      | 0.95 mW                                  |
| Spot Area                  | $50 \mu\text{m} \times 2000 \mu\text{m}$ |
| Repeatability              | $0.025 \mu\text{m}$                      |

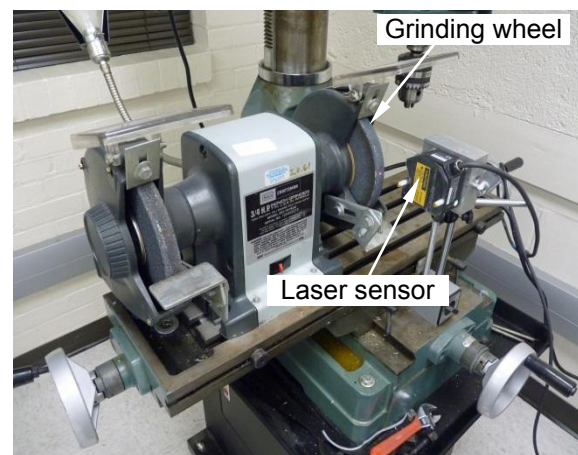


FIGURE 3. A close view of grinding wheel and laser sensor.

FIGURE 3 shows a close view of grinding wheel and laser sensor. A bench grinder was bolted to a mill table. In front of the grinder, the CCD laser displacement sensor was mounted to a magnetic indicator mount which was in turn affixed to the mill base. The mill table and the magnetic indicator mount provided articulation of the laser displacement sensor head as well as positional adjustments along X, Y, and Z axes to achieve the requisite 50mm spacing between the laser sensor and the grinding wheel surface.

The grinder used was a 115 Volt, 60 Hz, 0.75 H.P. Craftsman 257.191500 with a nominal rotation speed 3580 rpm. The grinding wheel used was a Craftsman Vitrified Aluminum Oxide 7" diameter, 0.75" wide, fitting a 0.5" shaft. The

wheel surface abrasives are classified as 60 grit and N Grade.

### **Data Collection**

The laser sensor was setup, energized, and then allowed to warm up for twenty minutes. Thereafter, laser sensor sampling speed and duration are set. The grinding wheel was powered on and allowed one minute to assure that it reaches an idle speed. At this point, three sets of data are collected in succession.

The laser displacement sensor directed at the grinding wheel measures the distance to points on the wheel surface hundreds of times during each revolution of the grinding wheel. Once uploaded to the DAQ system, these points can be interpreted as the wheel surface shape and topography. After being uploaded to the DAQ, the data was analyzed to generate a surface profile of the wheel. Further data analysis was conducted to develop a means of calculating the wheel's G-Ratio empirically. Finally, a method for increasing the power of the sampling scheme based on the sampling rate and wheel rotational speed is developed.

Due to the dull finish of vitrified Aluminum Oxide however, the reflected light was insufficient to sample faster than 50 kHz. Therefore, the process was first completed with a sampling rate of 20 kHz and then repeated with a sampling rate of 50 kHz. Data for each set was collected for one second, yielding 20,000 points for each of the first three trials and 50,000 points for each of the second three.

## **RESULTS AND DISCUSSION**

### **Surface Profile**

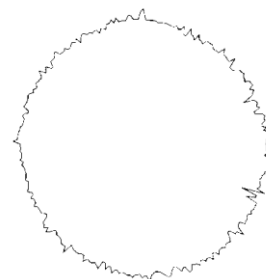
The primary benefit of generating a grinding wheel surface profile is to be able to monitor the topography of the wheel in real-time in order to make informed decisions about the quality of the wheel surface and respond based on the anticipated impact of the topography on grinding capability. Therefore, it is desirable to achieve an extremely high sampling rate in order to generate as detailed a surface profile as possible. The number of data points generated per rotation from a wheel with rotational speed  $N_s$  rotations per second and using a sampling frequency of  $s$  samples per second is approximated by

$$M' \cong \frac{s}{N_s} \quad (1)$$

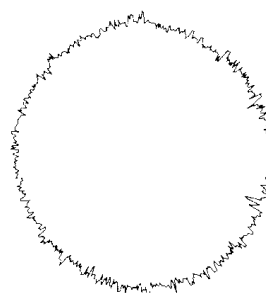
The number of data points collected in the 20 kHz trial and 50 kHz trial, by Equation (1) are predicted to be approximately 335 and 838. Once uploaded to the DAQ, the data is copied to Microsoft Excel.

In Excel, a single rotation of the wheel was selected at random. The average of the data set was determined to be 194.5  $\mu\text{m}$  and 210.2  $\mu\text{m}$ . This value was subtracted from each measurement, in effect establishing zero displacement as wheel mean height, and transforming other measurements to displacement relative to this mean.

After the transformation to a mean height of zero, the median wheel height and sample standard deviation were determined to be -5.1  $\mu\text{m}$  and 90.14  $\mu\text{m}$  for 20 kHz test and -2.6  $\mu\text{m}$  and 92.3  $\mu\text{m}$  for 50 kHz test. As for the 20 kHz test, the maximum surface height is 364.5  $\mu\text{m}$  and the minimum surface height is -443.3  $\mu\text{m}$ . As for the 50 kHz test, the maximum surface height was 368.6  $\mu\text{m}$ , and the minimum was -457.1  $\mu\text{m}$ . The two datasets are then plotted as radar charts as shown in FIGURE 4 and FIGURE 5.



**FIGURE 4.** The wheel profile generated at 20 kHz sampling rate.



**FIGURE 5.** The wheel profile generated at 50 kHz sampling rate.

From FIGURE 4 and FIGURE 5, it can be seen that the overall surface profiles obtained from 20 kHz sampling rate and 50 kHz sampling rate are in general agreement with each other. Despite their overall similarity, there clearly is a more detailed profile generated at the 50 kHz sampling rate. It is possible that with wheels of different material that even a 50 kHz sampling rate would not be supported by their low reflectance. Conversely, a more reflective wheel could support higher sampling speeds and an even more detailed surface profile.

Additional consideration must be given to wheel rotational speed. Equation (1) demonstrates the proportional loss of measurements per rotation as the rotational speed increases. A high rate of rotation could potentially conceal large aberrations in the wheel surface.

### **Discussion of Enhanced Sampling Scheme**

Except for cases in which the number of samples recorded per second is an integer multiple of the number of wheel revolutions per second, succeeding revolutions of the wheel will not yield duplicate measurements, but rather a distinct set of measurements offset by some distance. Given a wheel's diameter, rotational speed, and a sampling rate, these sets may be combined to yield one cohesive "superset" of data.

It is first assumed that a grinding wheel of diameter  $d$  rotates at a constant speed of  $N_s$  rotations per second, and that this grinding wheel will be sampled  $s$  times per second. In such case, the number of measurements per rotation,  $M'$ , is considered to be exactly given by Equation (1)

$$M' = \frac{s}{N_s} \quad (2)$$

Unless  $s \text{ Mod } N_s = 0$ , there will be some decimal which represents "a fraction of a measurement" between the final measurement of the given rotation and the initial measurement of the same rotation. It is defined that the last measurement,  $M$ , as the greatest integer less than or equal to  $M'$ .

This fractional measurement can be converted to a time which elapses between the  $M^{\text{th}}$  measurement, defined to occur at position  $x_{M-1}$

and the initial measurement, occurring at  $x_0$  by the function

$$\frac{(M' - M)}{s} = t_a \quad (3)$$

It follows from Equation (3) that the time which elapses after passing the position of the initial measurement of a given rotation and before the initial measurement of the next rotation is

$$\frac{1 - (M' - M)}{s} = t_b \quad (4)$$

The product of the rotational speed of the wheel and the wheel's circumference,  $\pi d$ , is equal to the surface speed of the wheel past the sensor beam. When this product is multiplied by the factor of  $t_b$ , the result is the distance by which the initial measurement of rotation  $n$  follows the initial measurement of the preceding rotation,  $n-1$ .

$$t_b N_s \pi d = \delta \quad (5)$$

At some point,

$$n\delta = \frac{1}{s} N_s \pi d \quad (6)$$

Since the surface speed of the wheel occurs both as a factor of  $\delta$  and on the right hand side of the above equation, the above reduces to

$$nt_b = \frac{1}{s} \quad (7)$$

Solving for  $n$ , and simplifying,

$$n = \frac{1}{1 - (M' - M)} \quad (8)$$

Since  $n$ , the rotation count, is an element of the set of integers, in the case where the  $n$  obtained is not an integer, denoted below as  $n'$ , a correcting integer factor,  $k$ , must be introduced in order to yield an integer value of  $n'k$ <sup>1</sup>.

$$n'k = \frac{1}{1 - (M' - M)} \quad (9)$$

---

<sup>1</sup> A close approximation of an integer value for  $n'k$  will not result in a fully enhanced data set, and although enlarging the dataset, will actually introduce an additional offset analogous to the initial.



In the case where Equation (8) yields an integer value of  $n$ ,  $k=1$ , At the completion of  $n \cdot k$  rotations, the measurement occurring at position  $x_{n \cdot k M}$  will also occur at the position  $x_0$ , and the whole cycle begins anew.

Application of the above analysis will yield a dataset for the wheel surface which consists of  $n \cdot k M - 1$  points as opposed to  $M$  points. This more detailed wheel topography may serve to enhance decision making as well as enable more powerful analysis from data collected using slower sampling schemes. In addition, the detailed wheel topography will enable machinists to monitor the suitability of the grinding wheel in situ. This will in turn minimize scrap and minimize unprofitable machining time.

### **Discussion of Tracking G-ratio**

In grinding process, the G-ratio is defined as the ratio of the volume of material removed from the workpiece to the amount of material sacrificed by the grinding wheel [1].

$$G - Ratio = \frac{[Change\ in\ workpiece\ volume]}{[Change\ in\ wheel\ volume]} \quad (10)$$

Wheel volume,  $v_w$ , may be initially determined by stated specifications or actual measurement. The volume of the wheel can be treated as the volume of a cylinder with radius equal to wheel radius,  $r$ , and height of wheel width,  $w$ .

Where  $r_i$  is the initial radius and  $r_j$  is the radius at some later point in time, the change in wheel volume is given by

$$\Delta v_w = \pi w (r_i - r_j)^2 \quad (11)$$

In Equation (11) above,  $r_i$  is the initial mean wheel height as indicated by the laser displacement sensor, and  $r_j$  is the mean wheel height measured at some later point in time. Therefore, given an amount of material removed from workpieces,  $v_p$ , the G-Ratio may be empirically determined as

$$\frac{v_p}{\Delta v_w} \quad (12)$$

From preliminary measurement results, the laser displacement sensor can be used to track differences in mean distance to wheel surface (i.e. changes in the wheel's radius). The change in grinding wheel radius can be used to calculate

the change in grinding wheel volume. Therefore, the proposed measurement method also helps to track grinding ratio (G-ratio) for any particular grinding process and grinding wheel with unprecedented precision.

### **CONCLUSIONS**

In this study, an ultra high-speed/high-accuracy CCD laser displacement sensor is shown to be a proficient method of generating and monitoring the surface topography of a grinding wheel.

Wheel rotation speed and sampling rate were shown to be the two factors which determine the amount of data available from a wheel rotation. Slower wheel rotations and faster sampling rates will increase the data gathered. Sampling rate, however, is restricted by the reflectance of the grinding wheel.

As datasets collected by the laser displacement sensor are analyzed, changes in the wheel's mean profile height may be interpreted as changes in wheel volume. This allows for the determination of a situation specific G-Ratio based on any variety of grinding activity that may be undertaken.

### **ACKNOWLEDGEMENTS**

This research work was supported by the National Science Foundation through the CAREER Award CMMI-0953502 (Supplement of Research Experiences for Undergraduates).

### **REFERENCES**

- [1] Malkin S, Guo C. Grinding Technology: Theory and Application of Machining with Abrasives. 2<sup>nd</sup> Edition. Industrial Press, Inc. New York, NY: 2008.
- [2] Law S, Wu S. Simulation Study of the Grinding Process. Transactions of the ASME Journal of Industrial Engineering. 1973; 95: 972-977.
- [3] Blunt L, Ebdon, B. The Application of Three-Dimensional Surface Measurement Techniques to Characterizing Grinding Wheel Topography. International Journal of Machine Tools and Manufacture. 1996; 36: 1207-1226.
- [4] Chen X, Rowe W. Analysis and Simulation of the Grinding Process. Part 1: Generation of the Grinding Wheel Surface. International Journal of Machine Tools and Manufacture. 1996; 36: 871-882.

# GEOMETRICAL AND MATERIAL MODIFICATION OF STAINLESS STEEL AND ALUMINUM ALLOY SURFACES INDUCED BY FINE BURNISHING PROCESS

Hidetake Tanaka<sup>1</sup>, Kazuhisa Yanagi<sup>1</sup>  
<sup>1</sup>Department of Mechanical Engineering  
Nagaoka University of Technology  
Nagaoka, Niigata, Japan

## ABSTRACT

This study deals with a surface modification phenomenon in a cylindrical surface finishing process using diamond burnishing tools. The burnishing process is a micro-plastic machining method, in which a spherical diamond point tool compresses the metal surface to obtain a mirror-like surface roughness; it could improve surface layer hardness similarly to the shot-peening process. In this report, we try to evaluate the surface modification in the burnishing process using the nanoindentation technique and an X-ray residual stress measuring instrument owing to the extremely thin surface layer. From the experimental result, the hardness of the surface layer is improved (by at least 100 HV) and a significant residual stress (-700MPa) remains on the surface layer of the burnished workpiece.

## INTRODUCTION

In the case of hardened steel, long machining time is required for high grade surface finish by abrasive grinding. Recently, the diamond burnishing process has been utilized and replaced conventional grinding as an advanced surface finish method [1]. The burnishing process is one of micro plastic working, where a spherical diamond point tool compresses the metal surface to obtain a mirror-like surface roughness finish and it reduces the environmental disturbances such as grinding sludge and machining fluid. Moreover, the burnishing process can improve surface layer hardness like shot-peening process. The

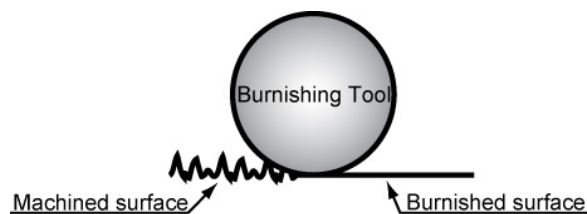


FIGURE 1. Mechanism of burnishing process

influence of workpiece surface texture on the following burnishing process and the estimation of change in workpiece diameter were made clear through our previous studies [2][3]. On the other hand, properties of surface modification by burnishing process are not considered. Evaluating the modification on the surface is difficult, because thickness of the expected modified layer is quite thin (less than 5 $\mu$ m). We tried to evaluate the modification of improved properties on the burnishing surface by using of nanoindentation technique and X-ray residual stress measuring instrument.

## BURNISHING PROCESS

### Mechanism and advantages

A spherical/hemispherical shaped diamond chip is compressed to metal surface and then it is traversed with turning the surface in order to obtain mirror-like surface finish as illustrated in Fig. 1. Advantages of such burnishing process are summarized as follows:

- Quick change from a rough surface to a mirror-like surface of  $R_z$  0.1-0.8 $\mu$ m.
- Hardening effect and increase in wear resistance [4][5].
- Low emission.

### Burnishing tool

In the study, a diamond chip type burnishing tool

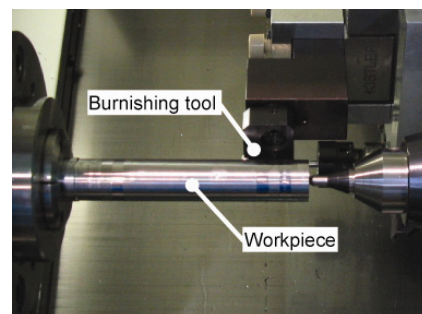


FIGURE 2. Practical burnishing with NC lathe

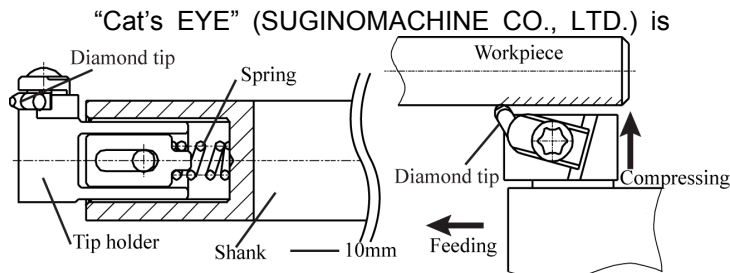


FIGURE 3. Configuration of diamond burnishing tool

used. The tool holder can exchange instead of a commercial turning tool as shown in Fig. 2. A diamond chip burnishing tool can perform an arbitrary pressurizing. A spring is built in the chip holder and tool holder as shown in Fig. 3. The diamond chip is SCD (Single Crystal Diamond) of the throw away method, in order to exchange when abrasion or damaged.

### Preset burnishing force

A burnishing tool has mechanism for changing pressurizing of built-in spring according to the kind of workpieces. The specifications of three kinds of springs used with the burnishing tool are shown in Table 1. Pressurizing is set to the spring beforehand; in this study, spring constant is decided considering the hardness of the workpiece.

TABLE 1. Specifications of springs

|                              | Spring025 | Spring086 | Spring166 |
|------------------------------|-----------|-----------|-----------|
| Spring constant (N/mm)       | 25        | 86        | 166       |
| Maximum preset force(N)      | 98        | 206       | 332       |
| Maximum spring shrinkage(mm) | 4.0       | 2.4       | 2.0       |

TABLE 2. Workpiece materials and mechanical properties

|                 | Mechanical properties |                      |
|-----------------|-----------------------|----------------------|
|                 | Vickers hardness[HV]  | Young's modulus[GPa] |
| Stainless steel | 200                   | 193                  |
| Aluminum alloy  | 170                   | 71                   |

TABLE 3. Turning conditions and surface roughness of workpiece

|                         | SUS316 | A7075 |
|-------------------------|--------|-------|
| Cutting speed (m/min)   | 125    | 144   |
| Depth of cut (mm)       | 0.3    |       |
| Feed rate (mm/rev)      | 0.16   |       |
| $R_a$ ( $\mu\text{m}$ ) | 1.29   | 1.38  |
| $R_z$ ( $\mu\text{m}$ ) | 5.94   | 4.93  |

## EXPERIMENTAL PROCEDURE

### Machine tool and instruments

In the study, stainless steel (X5CrNiMo17-12-2) and aluminum alloy (AlZn5.5MgCu) are selected as workpieces whose shape is solid-core round bar and diameter is 20mm and length is 150mm. The mechanical property of workpieces is shown in Table 2. The burnishing experiment is carried out by using of a NC lathe(TAKAMATU MACHINERY CO., LTD; CNC Precision lathe X-10) with non-chlorine cutting oil((IdemitsuKosan CO., LTD.; DAPHNE LA20) while burnishing process.

### Turning conditions

Workpieces of stainless steel and aluminum alloy are turned before burnishing process by using cemented carbide chip(Tangaroy CO. LTD.; TH10). For preparing processing conditions are set targeting to become  $1.0 \mu\text{m}$   $R_a$  on the surface. Selected turning conditions and obtained workpiece surface texture parameters are shown in Table 3 and measured profiles are shown in Fig. 4.

### Burnishing conditions

Finished surface texture depends on the burnishing conditions. Unoptimized conditions can incur rough surface finishing. Thus, the burnishing conditions are carefully decided according to the fundamental experimental result based on the experimental design. [6] For all, spindle rotation speed is fixed at  $800 \text{ min}^{-1}$  as burnishing common condition. The following burnishing conditions are prepared.

- Stainless steel : Feed rate 0.05mm/rev, Burnishing force 65N
- Aluminum alloy : Feed rate 0.075mm/rev, Burnishing force 30N

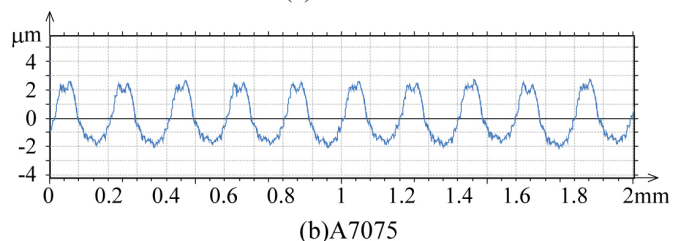
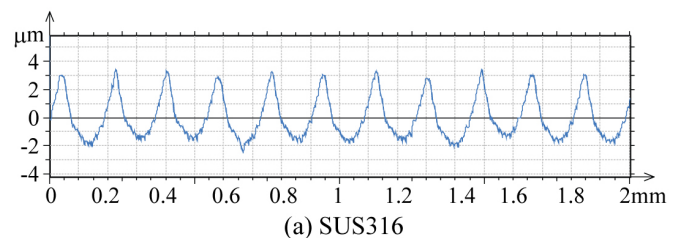


FIGURE 4. Measured roughness profiles after turning

## EXPERIMENTAL RESULTS

### Surface roughness

Burnished surface are measured by surface texture measuring instrument. Considered surface roughness parameter;  $R_a$  and  $R_z$  are shown in Table 3. The measured profile on the turned surface is shown in Fig. 4. Fig. 5 shows the measured profiles of the burnished workpieces. The measuring conditions are as follows;

- Instrument TOKYO SEIMITSU CO., LTD.  
; Surface Texture and Contour Measurement Instrument, SURFCOM3000A

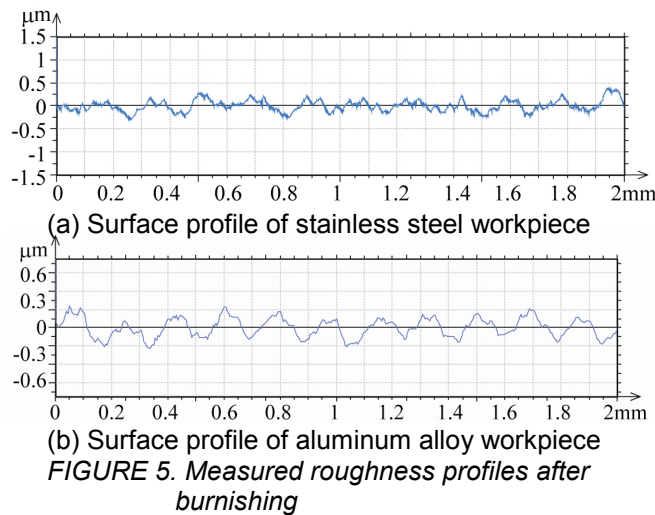


TABLE 4. surface roughness of burnished workpiece

|                         | SUS316 | A7075 |
|-------------------------|--------|-------|
| $R_a$ ( $\mu\text{m}$ ) | 0.09   | 0.08  |
| $R_z$ ( $\mu\text{m}$ ) | 0.67   | 0.47  |

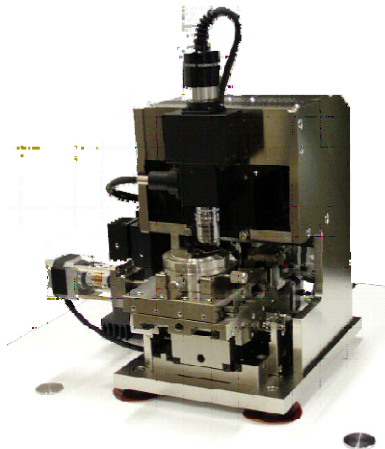


FIGURE 6. Nanoindentation apparatus

- Measuring conditions :  
evaluation length 2000 $\mu\text{m}$  with sampling distance 5 $\mu\text{m}$

From the measurement result, the phenomena that, the periodic undulated surface layer, processed by turning is transformed into the flattened surface by burnishing process are recognized. By comparing with roughness parameter,  $R_a$  is 1/10 improved before burnishing as shown in Table 4.

### Nanoindentation

#### Principle and apparatus

Because of thickness of the expected modified layer by burnishing process is quite thin (less than 5 $\mu\text{m}$ ), evaluation of hardness on the plastic deformation layer is difficult. Vickers test indenter penetrates the plastic deformation layer. Then, we tried adopting the nanoindentation technique.

The nanoindentation technique can measure the hardness of the microscopic region with high accuracy because it has the function minimum indenter, a super-low load, the low load resolution, and the low displacement resolution. The commercial apparatus "ENT-2100" (ELIONIX CO. LTD.) shown in Fig. 6 was used for nanoindentation tests in this study.

The following nanoindentation conditions are chosen.

- Stainless steel  
Load 10mN, Depth of push 300nm, Measuring points 10  
Load 20mN, Depth of push 450nm, Measuring points 10
- Aluminum alloy  
Load 1mN, Depth of push 120nm, Number of measuring points 5  
Load 5mN, Depth of push 300nm, Number of measuring points 5

Plural points of measurement for surface, one carried out and the results are assumed to take the mean value.

### Test results

The Vickers hardness obtained by the above-mentioned measuring condition is shown in Fig. 7. The Vickers hardness result of stainless steel is estimated about 510HV and its hardness is improved more than 300HV in comparison with the originally property. The Vickers hardness result of aluminum alloy is estimated about 260HV. The Vickers hardness is improved more



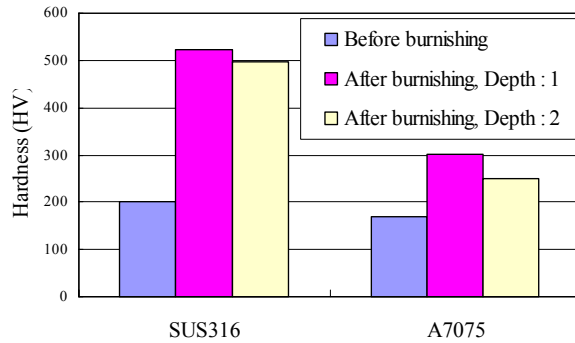


FIGURE 7. Obtained results of hardness

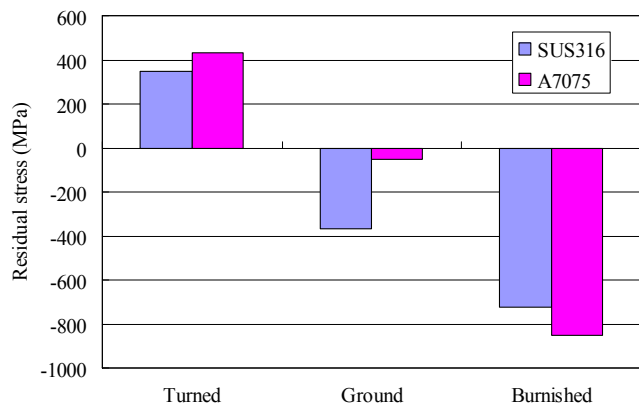


FIGURE 8. Obtained results of residual stress

than 90HV similarly. The facts clarify that hardness on the surface layer is modified by the plastic deformation by burnishing.

### Residual stress

In order to investigate the improvement of fatigue strength by the burnishing process, the residual stress measurement is carried out with X-ray stress analysis test by using of An X-ray residual stress analyzer(RIGAKUKIKI CO. LTD.; STRENFLEX MSF-2M). Measured surface compared to results of turned surface, ground surface, and burnished surface as shown in Fig. 8.

From the measurement result, the residual stress by burnishing surface issued relatively a far large value in comparison with the others. Burnishing process provided large compression force for the surface of the workpiece. Moreover, estimated residual stress indicates minimal value, because it aims compressively stress on the surface. Then, improvement of fatigue strength can be expected.

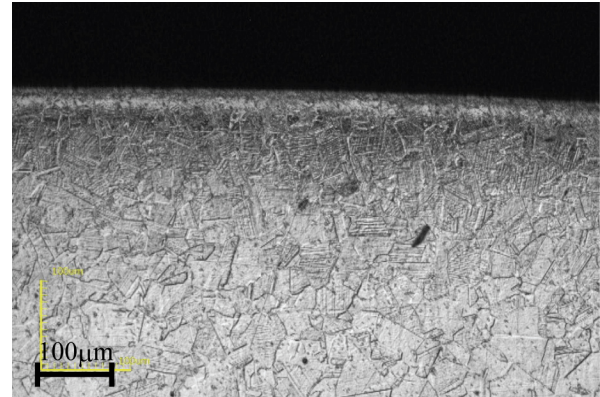


FIGURE 9. Laser microscopic image of SUS316

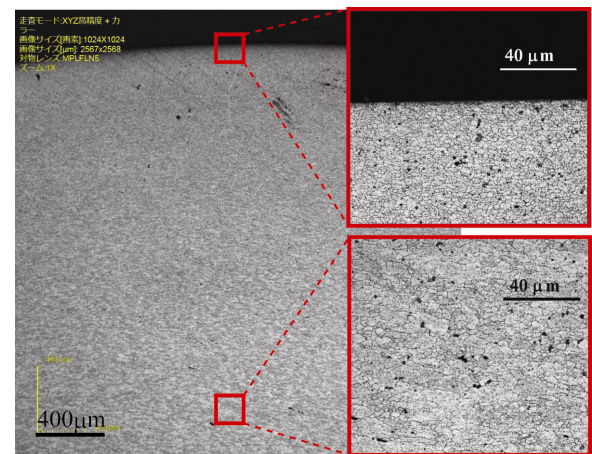


FIGURE 10. Laser microscopic image of A7075

### Surface layer observation

For reference, surface layer of burnished workpieces are observed by a laser microscope(OLYMPUS CO. LTD.; LEXT OLS4000). The observed specimens separated from burnished workpieces and polished, resinated and eroded are prepared. Laser microscopic images of the specimens are shown in Fig. 9 and 10. Modified layers having micronized grain boundary beneath surface are recognized especially in Fig. 9. From the observation result, the burnishing process having enough ability to modify surface layer by micro plastic deformation is demonstrated.

### SUMMARY

#### Concluding remarks

We examined the surface modification phenomena in surface finishing process on cylindrical workpieces by using a SCD burnishing tool and obtained the following concluding remarks.



- The plastic field caused by concentrated high pressure leads to work hardening of material and the hardness can be improved from 30% to 100% or more.
- Relatively high residual stress of compressibility was observed, and so certain improvement of fatigue strength may be expected.
- The burnishing process having enough ability to modify surface layer by micro plastic deformation is demonstrated by laser microscope observation.

## REFERENCES

- [1] N.S.M. El-Tayeb, K.O. Low and P.V. Brevern, "Influence of roller burnishing contact width and burnishing orientation on surface quality and tribological behaviour of Aluminium 6061", *Journal of Materials Processing Technology* 186, pp. 272-278, 2007.
- [2] Horoaki TABUTO, Hidetake TANAKA and Kazuhisa YANAGI, "A metrical study on cylindrical surface finishing using a diamond burnishing tool", *Proceedings of The 11th International Conference on Metrology and Properties of Engineering Surfaces*, pp. 315-319, 2007.
- [3] Wataru ISHII, Hidetake TANAKA and Kazuhisa YANAGI, "An analytical study on surface modification effect in burnishing process", *Proceedings of The Asian Symposium for Precision Engineering and Nanotechnology 2009*, 1P1-2
- [4] Toshiaki SEGAWA, Hiroyuki SASAHARA, Tatsuro ISHIKAWA and Masaomi TSUTSUMI, "Development of the Compressive Residual Stress Generating Cutter and Its Basic Performance", *J. Jpn Soc. Precision Eng.*, 70 6, pp. 853-857, 2004.
- [5] Faug-Jung Shiou, Chien-Hua Chen, "Freeform surface finish of plastic injection mold by using ball-burnishing process", *Journal of Materials Processing Technology* 140, pp. 248-254, 2003.
- [6] Glen Stuart Peace, "TAGUCHI METHODS A hands-On Approach", Addison-Wesley, 1993.

# ENGINEERED SURFACES CHARACTERIZATION METHODOLOGY

Ritwik Verma, and Jay Raja  
Department of Mechanical Engineering  
University of North Carolina at Charlotte  
Charlotte, NC, USA

## INTRODUCTION

In the recent years there has been an increasing interest in manufacturing products where surface topography plays a functional role [1]. These surfaces are called engineered surfaces and are used in a variety of industries like semiconductor, data storage, micro-optics, MEMS etc. Engineered products are designed, manufactured and inspected to meet a variety of specifications such as size, position, geometry and surface finish to control the physical, chemical, optical and electrical properties of the surface. As the manufacturing industries strive towards shrinking form factor resulting in miniaturization of surface features, measurement of such micro and nanometer scale surfaces is becoming more challenging. Great strides have been made in the area of instrumentation to capture surface data, but the area of algorithms and procedures to determine form, size and orientation information of surface features still lacks the advancement needed to support requirements of R&D and high volume manufacturing industries.

## CHARACTERIZATION METHODOLOGY

Several contact and non-contact instruments are available with sub nanometer vertical and sub micron lateral resolution to measure topography of the surface. Measured data is then analyzed using available techniques to characterize the surface.

The most common and standard technique till date for assessing surface characteristics is doing two dimensional analysis on three dimensional surfaces [2][3]. The procedure to determine basic geometrical dimensions using the existing techniques is a tedious and time consuming process and is dependent on human interaction resulting in poor measurement repeatability and reproducibility. Lack of advanced algorithms and automation procedures limits the capability of current techniques and hinders their use in high volume manufacturing and adds variability to the results. More significant limitation is the use of profile

information rather than surface to describe feature characteristics. ISO has recommended new definitions for calculating feature dimensions that are going to be the standards in the future and will find increased attention.

The process of characterization requires identifying features on the surface and then calculating parameters that describes the features and their relationship with each other. This task can be considered similar to the object recognition problem used in computer vision. We can use similar approach to advance surface characterization capabilities by providing more qualitative and quantitative description of imaged structural features. The challenge lies in using object recognition techniques from metrology perspective.

The objective of the research is to develop fast, repeatable, reproducible and flexible methodologies for measuring micro features at high resolution. This is accomplished by developing algorithms using image processing and geometric fitting techniques. ISO algorithms for calculation of size will be used as a foundation for calculation and reporting of results.

Figure 1 shows elaborate diagram of the components of the surface characterization methodology.

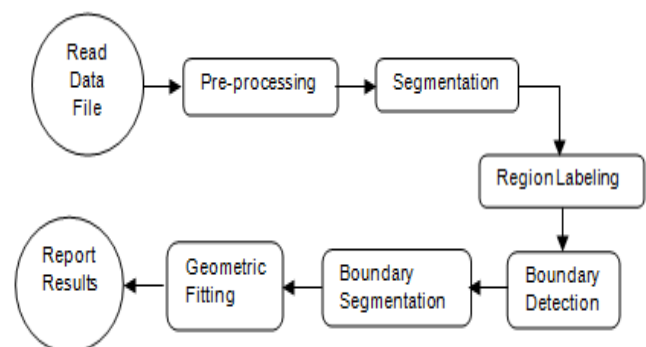


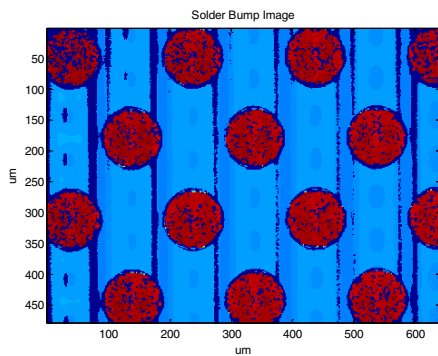
FIGURE 1: Steps in advanced characterization methodology

### **Read Data File**

The first step in the methodology is reading the data file generated by the measurement system. White Light Interferometer is a common tool used to measure engineered surfaces. The output file formats are DAT, OPD etc. SEM produces image file e.g. JPG. Vision CMM outputs a CSV file.

### **Pre-Processing**

After the camera captures an image of the part, the image is pre-processed to simplify subsequent operations without losing relevant information. Pre-processing an image could be required due to several reasons like edge effects; data drop out and noise in the data without compromising the integrity of the data. These components can cause error when calculating metrological characteristics in the Z axis. Figure 2 shows image of solder bumps in which 20% pixels are void due to either poor reflectance or high modulation threshold setting. There is significant data dropout in and around the perimeter of the bump which could result in inaccurate calculation of height and diameter.



**FIGURE 2: Bad or void pixel image**

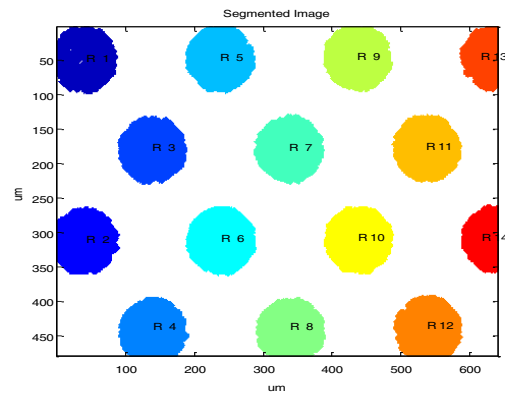
One way to approach the issue of data dropout is to use image morphology operations like dilation to fill the perforation in the data. This will ensure all the pixels belonging to the same region are well connected and will result in better segmentation. Morphological operations are used only to improve the quality of segmentation. Measured raw data is used for calculating feature dimensions.

### **Segmentation**

Image segmentation refers to partitioning an image into different regions that are homogeneous with respect to some image feature. After preprocessing the next step is performing the segmentation operation on the

surface. Segmentation subdivides an image into its constituent regions or objects. The level to which the subdivision is carried out depends on the problem being solved. That is, the segmentation should stop when the objects of interest in an application have been isolated. Segmentation is a very important part of the characterization. Segmentation accuracy determines the eventual success or failure of computerized analysis procedures. Segmentation can be classified into three categories (i) Pixel based (ii) Edge-based (iii) Region based [4]

Figure 3 shows image after segmentation showing 14 labeled regions.



**FIGURE 3: Bad or void pixel image**

Thresholding is suitable for patterned microstructures where the histogram is bimodal and threshold value can separate the microstructures from the substrate e.g. solder bump array, gratings etc. Clustering is useful when objects can be grouped based on some similarity measure. It can be used when features are of different size and geometry at different planar levels e.g. MEMS devices. Gradient based segmentation is used when the number of surface features is large and the features are at multiple planar levels. Surface normals are used when the surface feature is multi-faceted. Domain based segmentation is used when it is difficult to do the segmentation using height data. The height data is converted to another domain like FFT, Hough, Radon etc. After performing segmentation in the converted domain, inverse transform is performed to bring the data back in the height domain. This technique is used for micro-mirror and micro-pyramid array, to detect the base and slant edges.

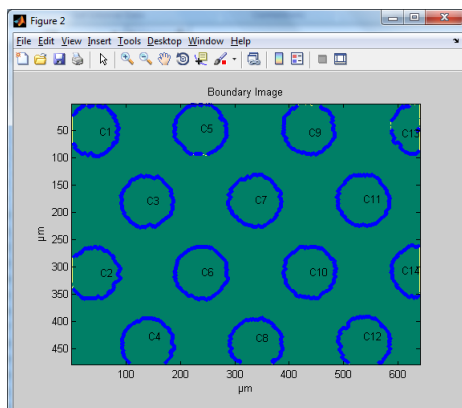
### **Region Identification**

After an image has been segmented into regions the next step usually is to represent and describe the aggregate of segmented raw pixels in a form suitable for further computer processing. Representing a region involves two basic choices: (1) representing the region in terms of external characteristic (its boundary), or (2) representing it in terms of its internal characteristics (the pixel comprising the region). Both the representations have its advantages. While the first one helps to calculate the orientation and size of the features the second one helps to find out the flatness, roughness and height of the features.

### **Region Boundary**

In edge detection the exterior boundaries of objects in the binary image is traced. The number of boundaries detected is equal to the number of objects in the image. Each boundary contains the row and column coordinates of a boundary pixel. Object boundaries are traced in either clockwise or anticlockwise direction. A boundary is created along the perimeter of each closed region.

Figure 4 shows the result of edge detection. A boundary is created along the perimeter of each closed region.



**FIGURE 4:** Bad or void pixel image

### **Edge Segmentation**

After region boundary detection the next operation is to divide a feature into line and curve segments. In this step each object boundary is divided into its constituent geometries like line, arc, and circle. Once objects are splitted into basic geometric elements then dimensional analysis can be performed. There are several methods available for edge segmentation.

Sugimoto and Tomita [5] proposed a new method for detecting the corner, inflection and transition points of a feature boundary by calculating the curvature and normal vector. Segmentation points fall in one of the three categories (i) Corner Point (ii) Transition Point (iii) Inflection Point. The algorithm for line segmentation if not optimized suffers from over-segmentation resulting in capturing even the insignificant transitions.

### **Geometric Fitting**

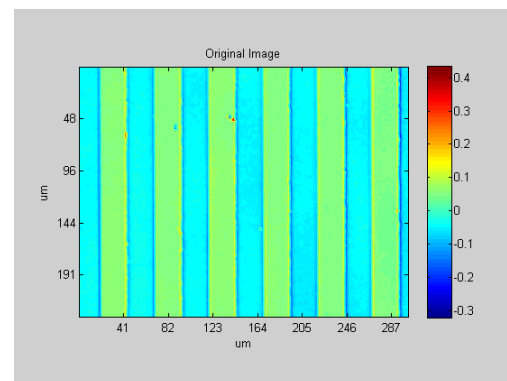
Least square geometric fitting is a mathematical procedure for finding the best-fitting curve to a given set of points by minimizing the sum of the squares of the offsets ("the residuals") of the points from the curve [6]. Once the boundary of features is segmented into line and curve segments, geometric fitting algorithms are applied to the line and curve segments.

### **Parameterization**

A comprehensive set of dimensional, geometric and textural parameters can be calculated at this stage. Measured features are geometric elements fitted to feature boundary. Constructed features are calculated using the measured features. The objective here is to extract necessary information in fast and automated way that can be used for making decisions about process improvements.

### **EXAMPLE**

Application of the methodology on an etched surface is shown in this section. Important parameters are trench width and depth.



**FIGURE 5:** Etched Surface

When calculating the etch uniformity, understanding metrological characteristics using multiple ways can provide deeper insight into the quality of etch. Several choices to determine the width and depth variation are shown below.

Caliper Distance: Point to point distance is used to calculate width of trench.

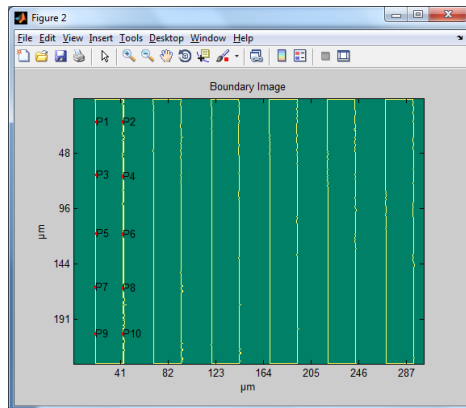


FIGURE 6: Caliper distance

Least Square Distance: Edge is partitioned and distance between point and least square line is calculated.

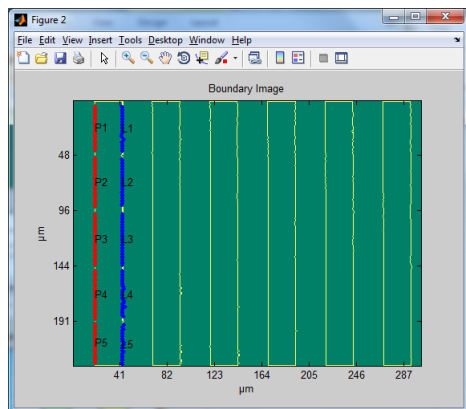


FIGURE 7: Edge partition distance

For calculating depth surface is partitioned and distance between average point to plane is calculated for each partition.

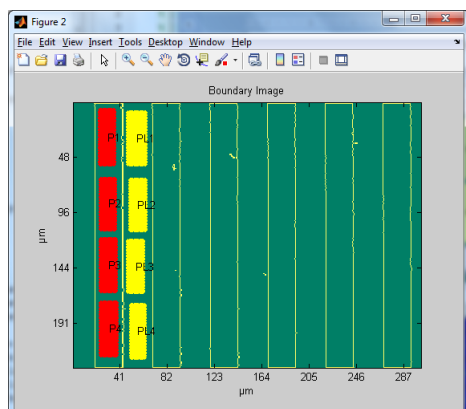


FIGURE 8: Point Plane Distance

## SUMMARY

The primary focus of the work has been the development of advanced techniques for characterization of engineered surfaces. Image processing and pattern recognition algorithms were refined and integrated with CMM type geometric fitting algorithms to solve metrological issues. Methodologies were created to characterize surfaces with simple and complex geometries. User can create recipes by choosing suitable options for the surface to automate the characterization thus decreasing the time required to obtain the form, size and orientation characteristics of the surface features. Multiple features can be processed simultaneously when the surface is patterned to get fast, repeatable, reproducible analysis of micro features at high resolution.

Algorithms developed can be used on surface data obtained from variety of measurement tools. These algorithms have been integrated in a toolbox developed in MATLAB environment. Toolbox can be used as a standalone application or part of any existing data analysis software.

## REFERENCES

- [1] Evans C, Bryan J, "Structured", "Textured" or "Engineered" Surfaces, CIRP Annals - Manufacturing Technology. 1999; v48, issue 2, 541-556.
- [2] ISO 4287, Geometrical Product Specification (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters. 1997
- [3] Stout K. et al., The development of methods for the characterization of roughness in three dimensions, European Report EUR 15178N, ISBN 0704413132. 1993
- [4] Gonzalez R and Woods R, Digital Image Processing (New York: Prentice Hall). 2002
- [5] Sugimoto K, Tomita F, Boundary segmentation by detection of corner, inflection and transition points, IEEE Workshop on Visualization and Machine Vision, Proceedings. 1994; 13-17
- [6] Forbes A, Least-Squares Best-Fit Geometric Elements, Division of Information Technology and Computing, NPL Report DITC.1989;140/89



# HIGH SPEED MILLING OF AN ALVAREZ OPTIC

Jennifer L. Lineberger<sup>1</sup>, Brian S. Dutterer<sup>1</sup>, Matthew A. Davies<sup>1</sup>

Paul Smilie<sup>2</sup> and Thomas J. Suleski<sup>2</sup>

<sup>1</sup>Mechanical Engineering Department

<sup>2</sup>Department of Physics and Optical Science

University of North Carolina at Charlotte

Charlotte, NC, USA

## INTRODUCTION

Single crystal diamond turning of “soft semiconductors”, such as germanium in the ductile mode, has been established [2] and has many uses for infrared devices. The goal of this work is to enable multi—axis contour machining of germanium and zinc selenide to generate freeform surfaces. The practical goal, which has driven the research, is the fabrication and testing of an Alvarez lens for the infrared regime. We believe this will be the first Alvarez lens, an optical device with many potential uses. The project involves: (1) the design of small scale milling tools with negative rake angles, which have not been previously available and tested in these materials; (2) testing to determine if ductile mode milling is achievable and under what conditions for these materials; (3) and the determination of milling parameters necessary for producing the needed surface finish and quality of freeform optics suitable for use in the infrared. While we have focused on germanium and zinc selenide for this project, the general results and approach are expected to be broadly applicable to other materials as well.

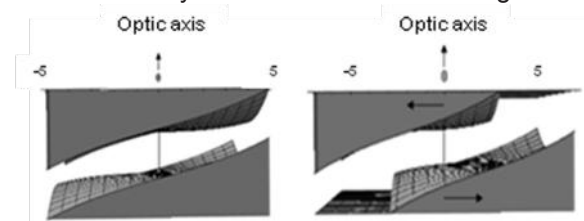
### Alvarez Lens

The Alvarez lens, invented in 1967 by Luis Alvarez, is a two-element lens, composed of two cubic phase plates, with the capability of variable focal lengths through lateral shifts [1]. Each cubic phase plate is composed of a flat surface on one side and an optical surface defined by a cubic equation on the other side (Eqn. (1)).

$$z(x, y) = 0.0012 \left( \frac{1}{3}x^3 + xy^2 \right) + 2.5 \quad (1)$$

Once assembled, the two cubic surfaces are inverted with respect to each other, aligned along the z-axis so that at each point the total thickness of the material along z is constant. Thus, if aligned in the x-y plane, the assembly acts as a plate of constant thickness with infinite focal length in z. When the plates are laterally shifted in the x-y plane, by an equal amount in

opposite directions, a composite spherical surface is created from the combination of the shifted cubic surfaces. The generated composite spherical surface changes by varying the amount of lateral shift in the x-y plane, changing the focal length of the system. The Alvarez lens system is shown below in Figure 1.



*FIGURE 1: Orientation of the Alvarez lens cubic phase plates when aligned (left) and shifted (right).*

As stated before, the goal of this work is to manufacture and test such a device in germanium, and later in zinc selenide, by diamond milling the freeform aspheric optical surfaces.

## MACHINING TESTS

In order to manufacture the Alvarez lens design, it is necessary to understand the contour milling behavior of each material. For this, a set of cutting experiments were designed and carried out using both turning (rotating part, stationary tool, no cut interruption, two axis motion) and milling configurations (rotating tool, interrupted cutting, three-five axes of motion). All cutting tests were completed using a spray mist of mineral oil for coolant. The materials for all cases were 27.5 mm diameter, single crystal germanium wafers and 30 mm diameter zinc selenide wafers. Prior to all testing, these wafers were mounted to the C-axis with a vacuum chuck and turned on one side, using the least aggressive of the parameter sets described below, to produce a planar optical surface perpendicular to the C-axis of the machine. The turning experiments, which have been reported

elsewhere in the literature for germanium [2-6], were completed in order to assist in the tool design and choice of parameters for the contour milling operations.

### **Turning Experiments**

#### **Turning Setup**

Based upon previous work in literature [2-6], a set of turning parameters intended to span the ductile and brittle modes of machining were developed and used for both materials. Surface speed was held constant at 1 m/s, while depths of cut varied between 1  $\mu\text{m}$  and 10  $\mu\text{m}$  for both materials, and the feed rate was varied between 0.3 micrometers per spindle revolution ( $\mu\text{m}/\text{rev}$ ) and 10  $\mu\text{m}/\text{rev}$ . Twelve bands were cut into each material using multiple combinations of the aforementioned parameters. Single crystal diamond tools, having nose radii of approximately 1mm and a  $-25^\circ$  rake angle, were used.

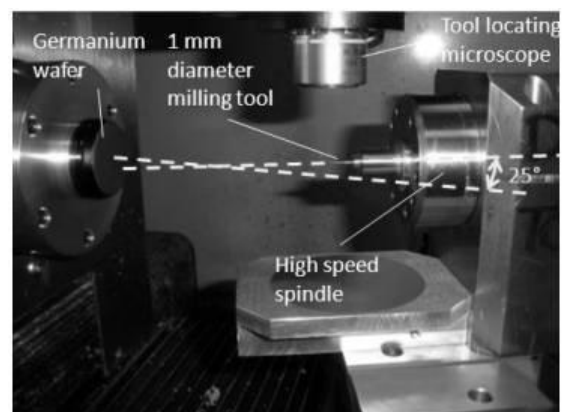
#### **Turning Results**

Turning experiments in germanium and zinc selenide showed that, consistent with existing literature, both materials can be machined in the ductile regime using a negative rake, single crystal diamond tool. Curiously, zinc selenide seemed to behave more favorably in the ductile regime and produced superior surface finishes below 0.5 nm  $R_a$ , that correspond quite well with theoretical prediction based on geometry alone.

### **Milling Experiments**

#### **Milling Setup**

For the milling experiments, 11 square patches were raster milled, using linear cutting movements directed toward the center of the wafer, with a constant step-over of 4  $\mu\text{m}$  perpendicular to the radius of the wafer. The first set of patches (patches 2-7) maintained a constant feed rate of 15 mm/min with varying depths of cut (0.001-0.015 mm) at a constant spindle speed of 50000 rpm and thus a constant cutting (surface) speed. The second set of patches (8-11) maintained a constant depth of cut of 0.002 mm with varying feed rates (50-500 mm/min). All cuts were completed using single flute, single crystal diamond milling tools, with approximately 1 mm nose radii and  $0^\circ$  rake angle and  $-45^\circ$  rake angle. Figure 2 shows the machining setup for the milling experiments.



**FIGURE 2:** Moore 350FG machining setup, showing the rotation axis of the high speed spindle and milling tool, tilted by  $25^\circ$  relative to the C-axis, on which the sample is mounted.

#### **Milling Results**

Milling tests showed that both germanium and zinc selenide can be milled with a zero rake angle tool, as has been reported by Davis et al.[7]. After milling with a zero rake tool, the surface finish was limited to approximately 20 nm  $R_a$ . But milling with a negative rake tool, better surface finishes were produced than those produced using a zero rake tool by approximately 25%. The disadvantage of using a negative rake angle micro-endmill is that the surface errors (since the tool projection is elliptical) are not as easily understood and compensated for as those produced from using a zero rake angle tool. For this reason, a zero rake angle micro-endmill was used for the fabrication of the prototype germanium optic. To better understand the surface errors caused by using a negative rake tool, two germanium milled samples (one milled with zero rake angle tool and one milled with negative rake angle tool) have been sent to Oklahoma State University for surface integrity measurements. Currently, we are still awaiting the results of these measurements so that it can be determined if one tool is causing more subsurface damage to the material than the other tool during the milling process.

### **ALVAREZ LENS**

#### **Alvarez Lens Tests Setup**

Through preliminary turning and milling tests, parameters to create the complex contoured surface of the Alvarez lens were determined. A single crystal, zero rake angle micro-endmill from Contour was used to raster mill all the optical components of the Alvarez lens. A feed

of 300 nm/rev, surface speed of 50,000 rpm, and a step-over of 4  $\mu\text{m}$  was used for each cubic phase plate. Each plate was machined in one process to reduce thermal errors, tool location errors, and any possible control loop errors.

### Alvarez Lens Machining Results

For the first cubic phase plate (Figure 3), manufactured in germanium, surface roughness analysis and surface measurements were taken to help determine the achieved surface finish and the actual machined surface.

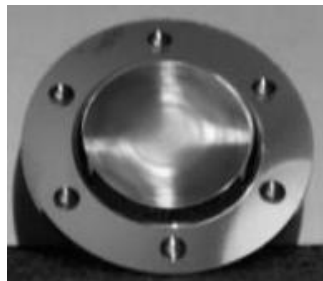


FIGURE 3: Germanium Alvarez lens cubic phase plate.

### Surface Finish Analysis and Results

Quantitative surface roughness measurements were taken across the surface of the first cubic phase plate. Nine different locations across the optic surface were measured in order to obtain an accurate average measurement of the surface roughness. To aid in eliminating error due to the surface curvature and stage tilt, fourth and lower order terms were removed in the measurement analysis. After examination in the scanning white light interferometer (SWLI), an average surface finish of 14 nm  $R_a$  or 17 nm RMS was achieved; where  $R_a$  values of approximately 2 nm were achieved along the tool feed paths. Average peak-to-valley was measured to be 122 nm, due primarily to the tool step-over.

From the SWLI data (Figure 4), it can be seen that the center of the optic contained the best surface finish (9 nm  $R_a$ ) and that the surface roughness increases gradually at the outer edges of the optic (16 nm  $R_a$ ).

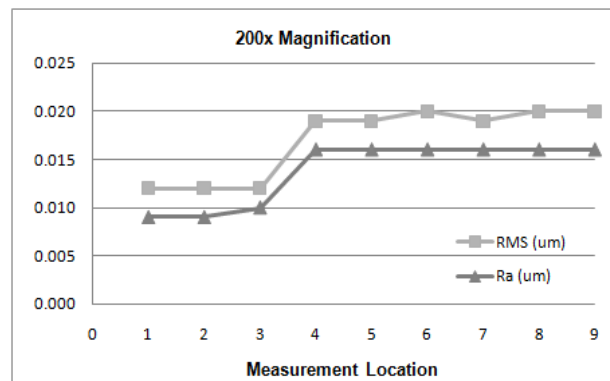


FIGURE 4: Germanium Alvarez lens surface roughness data: 200x magnification with 4<sup>th</sup> order removed.

### Surface Measurement Analysis and Results

Once the first Alvarez optic surface was machined and measured in the SWLI, the surface was then measured using a Leitz Coordinate Measuring Machine (CMM) to verify the contour of the surface. Four hundred data points were measured across the optic surface, in a 10 mm x 10 mm grid pattern, evenly spaced by 0.5 mm. Measurements were taken using a 3 mm ruby sphere probe. The collected data was imported into MATLAB for comparison with the theoretical surface equation (Eq. 1).

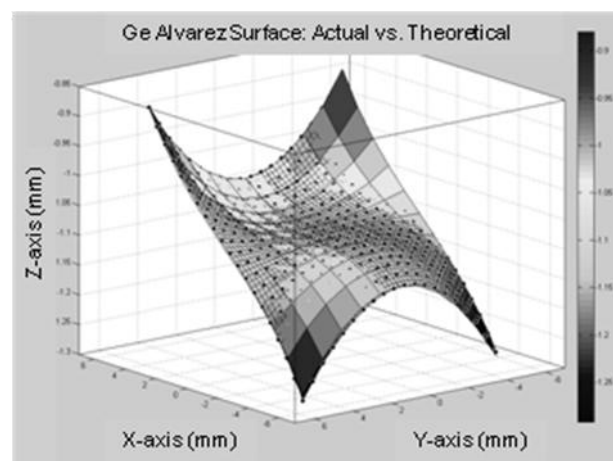


FIGURE 5: Germanium Alvarez cubic phase plate: Theoretical vs. Actual Surface.

Seen above in Figure 5, the “dotted” surface is the MATLAB generated surface fit to the CMM data. The solid surface was generated using the theoretical surface equation. Visually the two surfaces contain the same contour, having only variations on the order of 10 microns at the outer

extremities of the part, primarily due to a slight rotation between the measured data and the mathematical curve. MATLAB generated the following fit (Eqn. 2) to the experimentally measured data.

$$z(x,y) = 0.0004056x^3 + 0.00119xy^2 + 2.4 \quad (2)$$

Comparing Eqn. 1 and Eqn. 2, the coefficient for  $x^3$  should theoretically be 0.0004, and it was measured to be 0.0004056, creating an error of  $5.6 \times 10^{-6}$ . The  $xy^2$  coefficient was measured to be 0.00119 when it theoretically should have been 0.0012, an error of  $1.0 \times 10^{-5}$ . Finally, the standard error (root mean squared error) for this surface fit is 0.9999. These errors are small enough to not affect the overall focusing capability of the Alvarez optic, but may affect the comparison of measured and theoretical change in focal length as a function of shift; the behavior of the optic and will be reported in a later publication.

The second cubic phase plate has also been manufactured and the Alvarez optic is being assembled for testing. The second plate was not measured so to lessen the possibility of it being damaged before testing.

## Alvarez Lens Testing Results

### Custom Mounting

A custom mounting design was fabricated to enable a closer approach to the infrared camera, ultimately yielding results for a greater range of focal lengths. For testing, it was necessary for the cubic phase plates to be mounted to the translation stages in order to meet the strict alignment and lateral motion requirements of the optical design. To achieve this, a custom mounting assembly was designed and fabricated by Brian Dutterer. The custom mounts consisted of two right-angle brackets and mounting rings, where the rings were used to fasten the Alvarez plates to the brackets and aid in reducing the mechanical stress on the plates. The brackets were mounted on the translation stages, then the stages mounted onto another plate themselves. Once the Alvarez plates were mounted, they were aligned by touch-off measurements using the spherical seats machined into the plate area surrounding the cubic surface. Finally, the entire assembly, shown below in Figure 6, was set on a computer-controlled motion stage for taking measurements.



FIGURE 6: Entire assembly: SolidWorks model (left), close-up of mounts (middle), and entire assembly on the motion stage (right).

### Experimental Results

The Alvarez lens assembly was tested by locating the z-axis position for which the clearest images of the hot plate (infrared source) formed on the camera array, measuring the image distances for shifts ranging from 0.4 mm to 1.8 mm, using increments of 0.1 mm. Several measurements were taken by two different individuals for each amount of lateral shifts, using the average of those measurements as the experimental image distance. The locations at which the images started to blur, both farther and closer away from the location of the clearest image, were also measured as an experimental determination of error.

In order to compare the experimental data with the theoretical expectations, the focal length was calculated with respect to each measured image distance. For every image distance and corresponding “blur” distance, the focal lengths and errors were calculated using (Eqn. 3), where the constant 2540 mm is the approximate sum of the image and object distance. These were then compared to the theoretical focal lengths, calculated using (Eqn. 4).

$$f = [s_i (2540 - s_i)] / 2540 \quad (3)$$

$$f = 68.869 / d \quad (4)$$

A plot of the focal lengths is shown in Figure 7, where the “near blur” and “far blur” focal lengths were determined using (Eqn. 3), known as the minimum and maximum focal lengths. Theoretical focal lengths are also shown, determined using (Eqn. 4). It is evident that the measured focal lengths change dramatically with the lateral shifts in correspondence with the theoretical focal length variation.



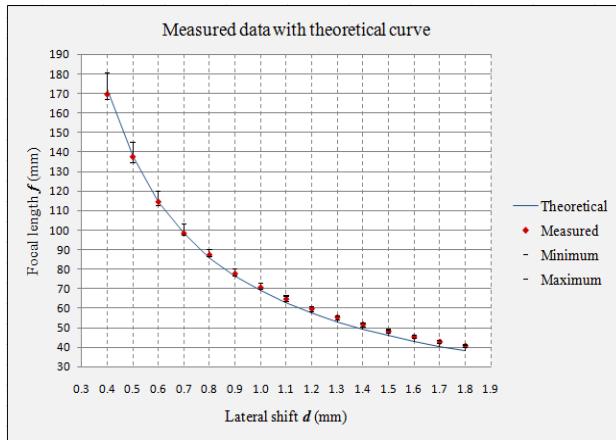


FIGURE 7: Comparison of experimentally and theoretically determined focal lengths.

In general, the variable-focus of the lens is confirmed. Looking at the measured data alone, the range from minimum to maximum focal length is much larger for smaller shifts (greater focal lengths), primarily due to the blur location measurements being a determination of the depth of focus of the lens and the depth of focus of the imaging system naturally increasing with the focal length. More significantly, the measured data is not in exact agreement with the theoretical curve. This is likely caused by the large depth of focus, where there is some uncertainty in the precise location of the clearest image. It is also seen that there are small discrepancies between the measured values and the theoretical curve, where the measured value is greater, leading to the conclusion that there is slight uncertainty in the object distance, actuator shifts, and the fact that the machined cubic phase plates have a 2.5 mm center thickness, whereas the theoretical calculation is based on a thin-lens approximation.

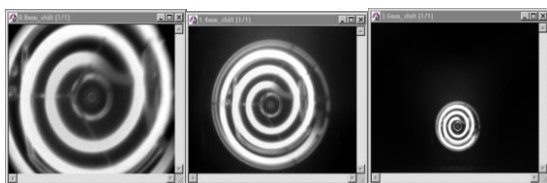


FIGURE 8: Hot plate images for  $d=0.4$  mm (left),  $d=0.7$  mm (center), and  $d=1.8$  mm (right).

Despite the small discrepancies, the performance of the Alvarez lens is excellent and high quality images of the hot plate were obtained for each shift (Figure 8). A surface

separation of approximately 0.4 mm was used and the slight aberration introduced within this separation was insignificant in terms of image quality. Since the lens had to be translated along the z-axis until a clear image formed with each shift, both the image and object distances changed, thereby changing the image magnification, as expected. The vertical shift of the image, with increasing lateral shift, is due to the fact that only one plate was shifted vertically, which introduced tilt in the vertical axis but this tilt had no effect on the focusing performance of the lens.

## CONCLUSIONS

A basic understanding of the machinability of germanium and zinc selenide has been gained through fundamental research and many trials of experimental machining and given us the knowledge needed for producing contoured surfaces, such as an Alvarez lens. A complete Alvarez lens has been machined in germanium, with an overall surface finish of approximately 14 nm  $R_a$ , where the machined surface contained minimal errors, on the order of  $10^{-3}$ , when compared to the theoretical surface. Actual surface errors at particular locations on the optic surface are being examined. It may be that the machined surface is better than the capability of the CMM. Eventually the goal is to measure the surface on the machine with an LVDT and develop an algorithm for a surface correction program that generates a corrected toolpath while the optic remains on the machine.

The Alvarez lens setup has demonstrated that the cubic surface design, originally proposed by Luis Alvarez, has the ability to produce variable focal lengths as a function of lateral shifts in the xy-plane. Looking beyond real-world testing, many insights were gained through the fabrication of this lens. While the lens is typically considered for performance at visible wavelengths with other materials, this concept has effectively been extended into the infrared wavelengths (3  $\mu\text{m}$  - 5  $\mu\text{m}$ ) with germanium. The results revealed that there is no significant difference in the behavior of the lens in the infrared regime, therefore allowing this lens setup to be considered for infrared applications, whereas it has not been considered before. Most important, the five-axis diamond milling method employed easily produced the required cubic surfaces in germanium, well within tolerance for achieving the expected optical



performance of the lens. Therefore, in terms of fabrication techniques, the milling method employed with the Moore Nanotech<sup>®</sup> 350 FG can effectively produce freeform surfaces in germanium, over a surface depth scale of hundreds of microns, that are adequate for performing a desired optical function.

Future optical design work involves further investigation of the concept of varying an optical function with lateral translation of freeform surfaces. The optical application currently being considered is laser beam shaping with an ultimate objective to design and manufacture a freeform surface for which lateral shifts would result in a beam shaping system with a variable diameter. Because of the simultaneous variability of both the phase and diameter of the incident beam, the surfaces will be complex and therefore applicable to the modeling, fabrication, and measurement approaches that we are using in this work. This design would be fabricated in zinc-selenide.

While we have focused on germanium and zinc selenide for this project, the general results and approach that were discovered are expected to be applicable to many other materials as well.

## ACKNOWLEDGEMENTS

We gratefully acknowledge II-VI Foundation's support of this research.

## REFERENCES

- [1] Alvarez, L.W. Two-element variable-power spherical lens, U.S. Patent 3,305,294. February 21, 1967.
- [2] Blackley, W. S. and R. O. Scattergood, Chip topography for ductile-regime machining of germanium, *Journal of Engineering for Industry, Transactions of the ASME*, 116(2), 263-266 (1994).
- [3] Blake, P. N. and R. O. Scattergood, Ductile-Regime Machining of Germanium and Silicon, *Journal of the American Ceramic Society*, 73(4), 949-957 (1990).
- [4] Yan, J., K. Maekawa, J. Tamaki, and A. Kubo, Experimental Study on the Ultraprecision Ductile Machinability of Single-Crystal Germanium, *JSME International Journal, Series C*, 47(1), 29-36 (2004).
- [5] Yan, J., K. Maekawa, J. i. Tamaki, and T. Kuriyagawa, Micro grooving on single-crystal germanium for infrared Fresnel lenses, *Journal of Micromechanics and Microengineering*, 15, 1925-1931 (2005).
- [6] Yan, J., Y. Takahashi, J. i. Tamaki, A. Kubo, T. Kuriyagawa, and Y. Sato, Ultraprecision machining characteristics of poly-crystalline germanium, *JSME International Journal, Series C*, 49(1), 63-69 (2006).
- [7] G. E. Davis, J. W. Robleeb, A. R. Hedges, Comparison of Freeform Manufacturing Techniques in the Production of Monolithic Lens Arrays, Preprint (2009).

# X-C-Z ULTRA-PRECISION MICROMILLING

Gregg E. Davis<sup>1</sup>, Jeffrey W. Roblee<sup>2</sup>, and Alan R. Hedges<sup>1</sup>

<sup>1</sup>II-VI Infrared

II-VI Incorporated  
Saxonburg, PA, USA

<sup>2</sup>Precitech

Ametek

Keene, NH, USA

## INTRODUCTION

In this paper we review some of our micromilling experiences using an ultra-precision lathe configured with X (linear), C (rotary), and Z (linear) axes, and a 50krpm milling spindle (Figure 1). This configuration is less common for micromilling than the X (linear), Y (linear), Z (linear) configuration, but it can be very effective at producing quality optical arrays and freeform structures. The purpose of this paper is to review some important considerations for micromilling in X-C-Z such as tool centration, work envelope, and toolpath programming. We will discuss the effects of tool centration on lenslet position and surface figure. We have observed that the size of the work envelope depends on several factors including the C-axis encoder, raster scheme and structure geometry. Strategies for mitigating set up errors will be presented and the practical limits of the work envelope will be explored. Finally, toolpath programming for X-C-Z machining will be discussed. Examples such as arrayed structures and freeform corrections will be used to illustrate programming complexities that must be overcome.

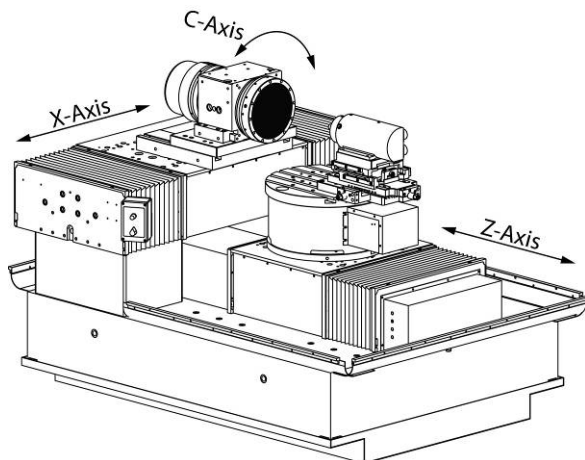


FIGURE 1. Lathe configuration for X-C-Z micromilling.

## X-C-Z TOOLPATH PROGRAMMING

When creating a toolpath for X-C-Z machining, surface geometry calculations are often performed in standard Cartesian coordinates, and then transformed to Machine X, Machine C, and Machine Z (Figure 2) coordinates. The x and y points are used to determine Machine X and C and the z point remains unchanged. A long list of these machine coordinates can be used to define a single Slow Tool Servo toolpath. For lens arrays and other repeated structures it is ideal to have one such subroutine that can be transformed to any number of programmed locations. This can be done in X-C-Z by defining each point in the local toolpath by three different machine variables, and defining each lenslet location by a separate set of three variables. The program can use all six of these variables to calculate the transformation to machine coordinates in real time. A custom file generator may be required to set up the program correctly.

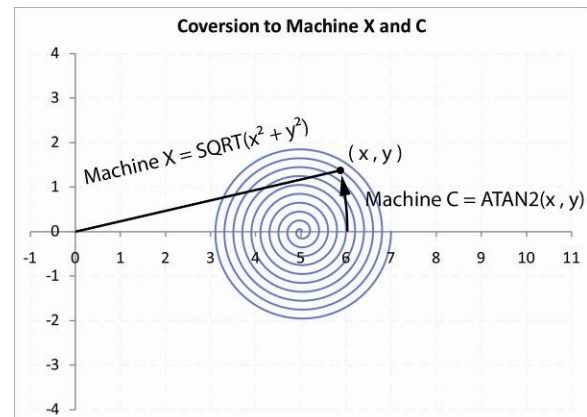
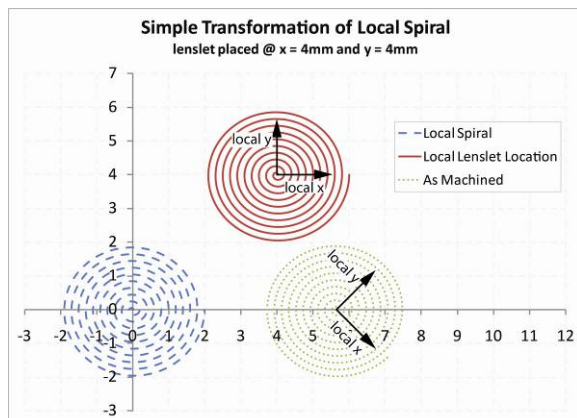


FIGURE 2. Machine variables are used to define an (x,y) point on a toolpath, which in turn is used to calculate Machine X and Machine C.

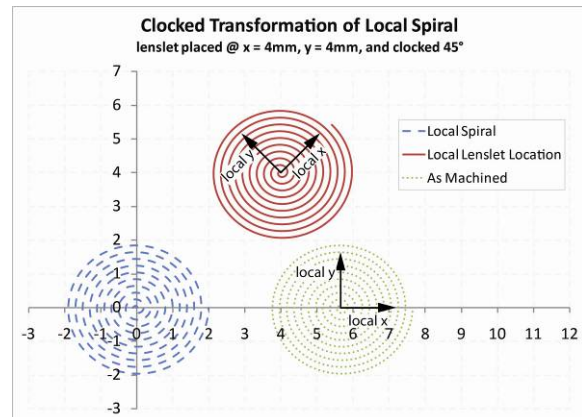
The transformation results in a positive Machine X so the milling spindle is always to the right of the work spindle. The resulting Machine C

coordinate places the toolpath point at the same height as the work spindle centerline.

Various transformation routines can be used. For example, simply adding offsets in x and y to a local spiral, results in an array of structures that have the same orientation on the substrate when completed. However, from the perspective of the milling spindle, the structures are clocked differently as they are being machined (Figure 3). This has consequences for freeform corrections since the motion is clocked differently for each lenslet. For a freeform correction to work, the motion should be oriented the same way for each lenslet from the perspective of the milling spindle. To achieve this, a clocked transformation can be used by adding an orientation angle to each offset location (Figure 4). The orientation angle should be calculated as a function of the lenslet location to eliminate human errors. Also, the error map used for feedback in the freeform correction needs to be taken at the same orientation as the local toolpath. Different corrections may be needed at different radial locations due to the slight change in motion of the machine axes.



**FIGURE 3.** This transformation results in each element of the array having the same orientation on the substrate. From the perspective of the milling spindle, the local toolpath will have a different orientation for different lenslet locations.

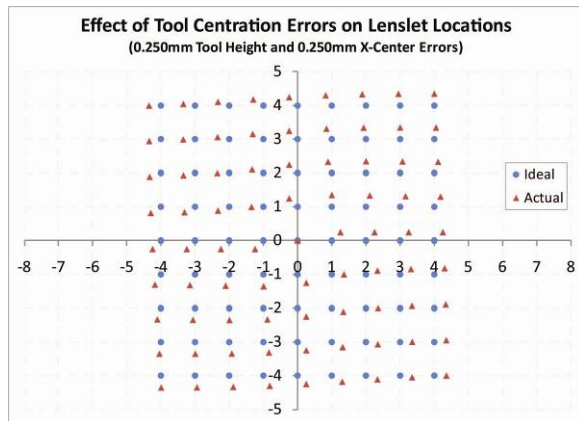


**FIGURE 4.** Clocking the local toolpath as a function of lenslet location orients the local toolpath the same way relative to the milling spindle for every lenslet location. This is useful when applying freeform corrections to the local toolpath.

## TOOL SETUP ERRORS

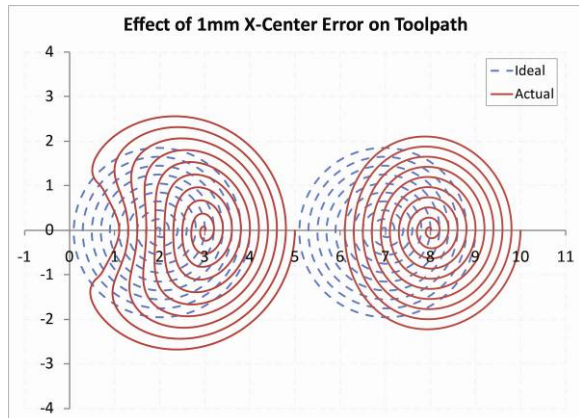
It is critical for the micromilling tool to be centered exactly with the axis of the work spindle. Errors in this alignment result in deviated lenslet positions and warped toolpaths. There are two components of tool centration error: X-Center (x-direction) and Tool Height (y-direction). The X-Center error can be adjusted by changing the X-zero position recorded on the machine controller. For machines without a Y-axis, the milling spindle must be mechanically raised or lowered to adjust Tool Height.

X-Center errors cause a radial shift in lenslet locations, and Tool Height errors cause a circumferential shift about the work spindle axis. Figure 5 shows an example array of locations that are shifted radially and circumferentially as a result of a 0.250mm X-Center error and a 0.250mm Tool Height error. Machining an array at some distance off-axis will result in near-uniform position deviations. Tool setup procedures have been developed to reliably achieve <0.5µm errors on Tool Height and X-Center.



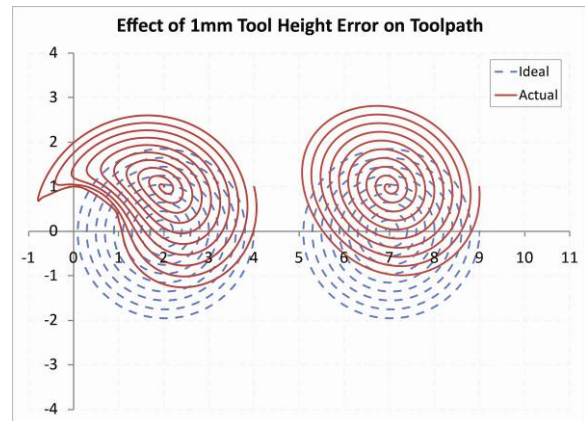
**FIGURE 5.** X-Center error causes a radial shift in lenslet locations while Tool Height error causes a circumferential shift.

There will also be an effect on surface figure since the toolpath becomes warped. Figure 6 shows the warping effect of a 1mm X-Center error at two off-axis locations. The warping effect decreases as the off-axis distance increases. Eventually, the warping effect becomes negligible and only the lenslet location shift is apparent (Figure 8). For X-Center error the warping generally results in  $0^\circ/90^\circ$  astigmatism.

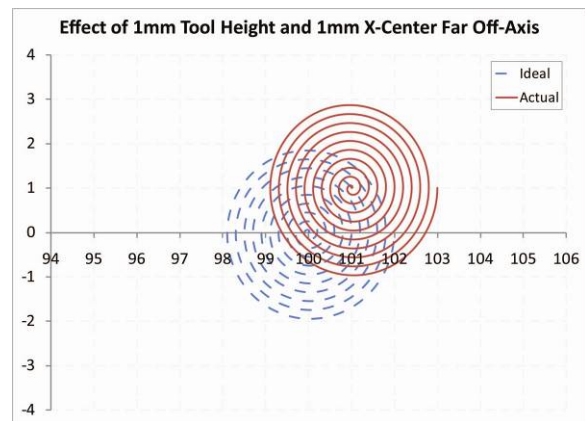


**FIGURE 6.** X-Center error causes warping of the toolpath. The general shape is  $0^\circ/90^\circ$  astigmatism that improves as off-axis distance increases.

Tool Height error also affects surface figure due to warping of the toolpath. Figure 7 shows the warping effect of a 1mm Tool Height error at the same two off-axis locations. The level of warping also decreases as off-axis distance increases (Figure 8). The general shape of the error is oriented  $45^\circ$  from the X-Center shape and results in  $45^\circ/135^\circ$  astigmatism.



**FIGURE 7.** Tool Height also causes warping of the toolpath. The general shape is  $45^\circ/135^\circ$  astigmatism that improves as off-axis distance increases.



**FIGURE 8.** Off-axis distance mitigates warping caused by Tool Height and X-Center. The position of the lenslet is still affected.

## PRACTICAL WORK ENVELOPE

The practical work envelope can be subjectively defined as the region where features of sufficient surface quality can be produced with sufficient placement accuracy. There are several factors that affect the size of this envelope in X-C-Z micromilling. The biggest limitation is the C-axis following error (CFE), and the detrimental effects of it increase linearly with radial distance. C-axis accelerations are typically low enough that large scale overshoots are within the band of subdivisional error (SDE) of the encoder. SDE comprises the majority of the error in C-axis position. The SDE tends to be the actual limitation and it mostly affects surface finish. Also, the CFE has frequency content based on the SDE of the C-axis encoder lines. Figure 9 shows CFE from two different encoders, one a Heidenhain 6000 line encoder and the other a Renishaw 16200 line encoder. The plot shows



both encoders rotating at 200 lines/sec. The C-axis does not have enough bandwidth to track SDE at 200 Hz so the errors show up as CFE in data gathers. The CFE resulting from the Renishaw appears to be about five times better than the Heidenhain. The improvement is better than the line count difference would suggest so there is improvement in interpolation as well. The frequency content shown in Figure 10 is also much improved. The twice per line count frequency, which is the most dominant, drops in power by more than an order of magnitude.

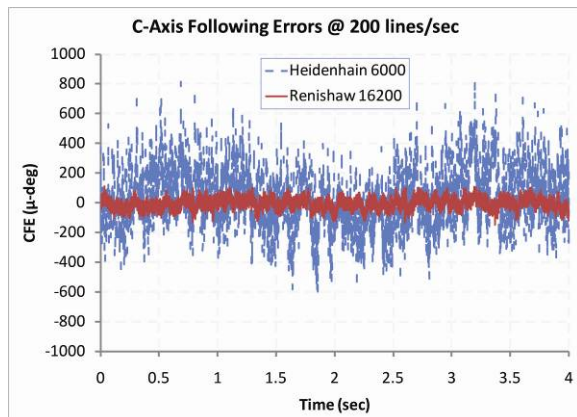


FIGURE 9. C-axis following errors can be reduced with improved encoder technology. This will extend the size of the practical work envelope.

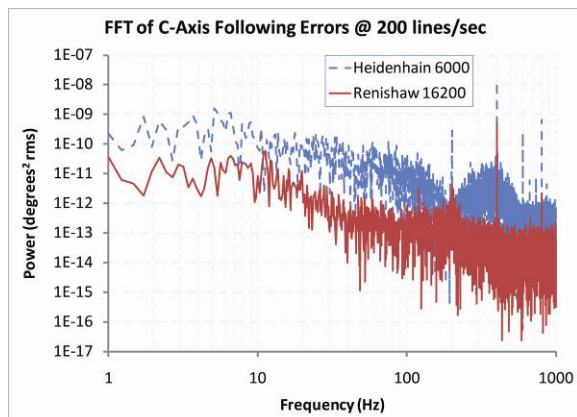


FIGURE 10. The frequency content of CFE shows the largest spike at the twice per encoder line frequency. At low C-axis velocities, the control will imprint this twice per line frequency into the C-axis motion.

The frequency content of the SDE is important because certain raster schemes, such as the local spiral, will have instances where the C-axis is nearly stationary and the encoder lines are passing through slow enough for the C-axis to

servo on the SDE. For the local spiral scheme, the C-axis is near-stationary at the 12 o'clock and 6 o'clock positions on a lenslet. The resulting effect is an hourglass patch of wavy finish that gets worse as off-axis distance increases. The magnitude of the waviness also increases with the slope in the circumferential direction. Figure 11 shows this effect on a series of lenslets (4mm diameter and 4mm concave radius of curvature) created with both encoders. The maximum slope in this example is 30°. The material used was an 8" diameter, ½" thick piece of OFHC copper.

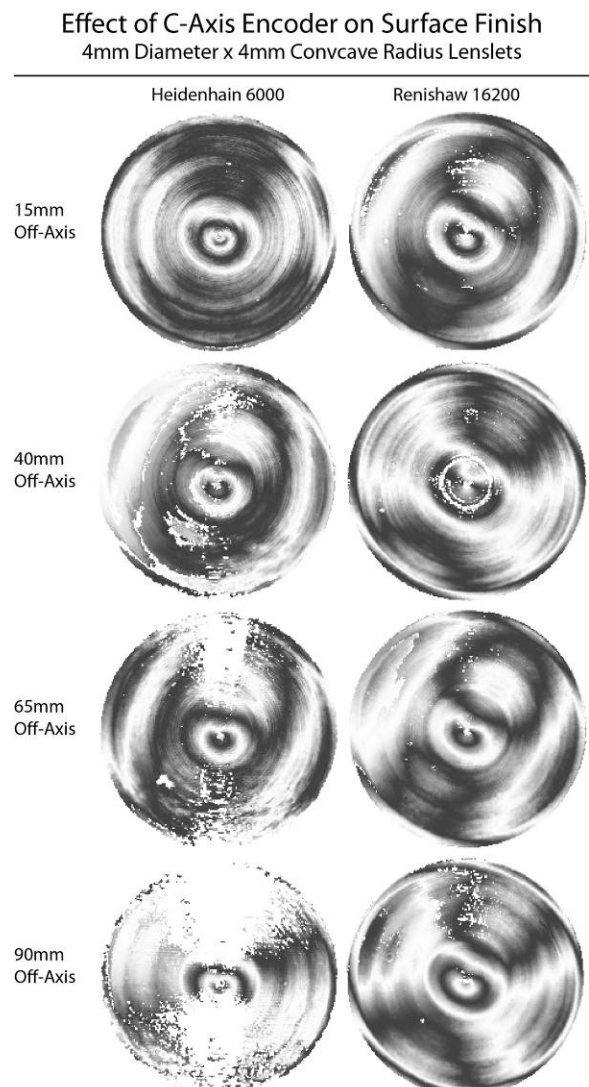
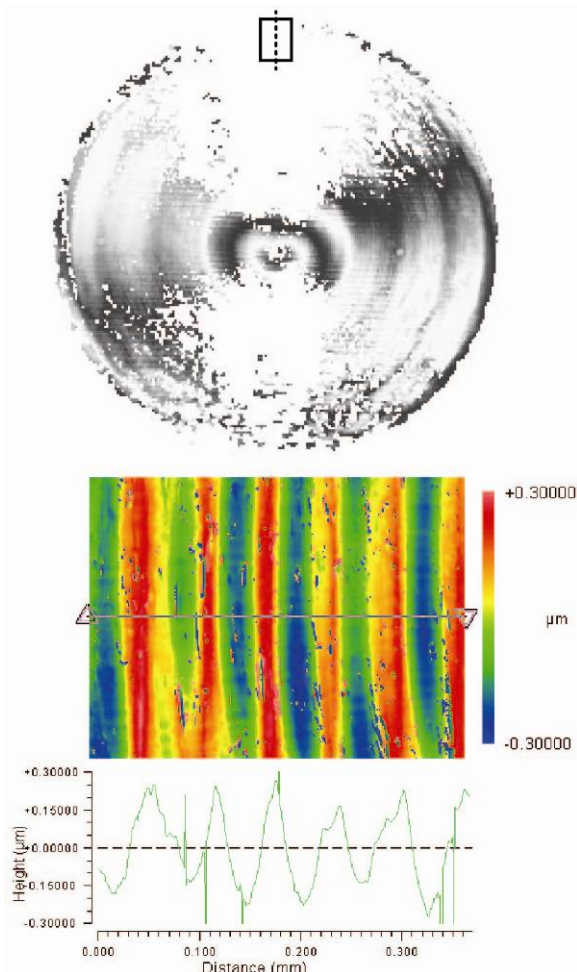


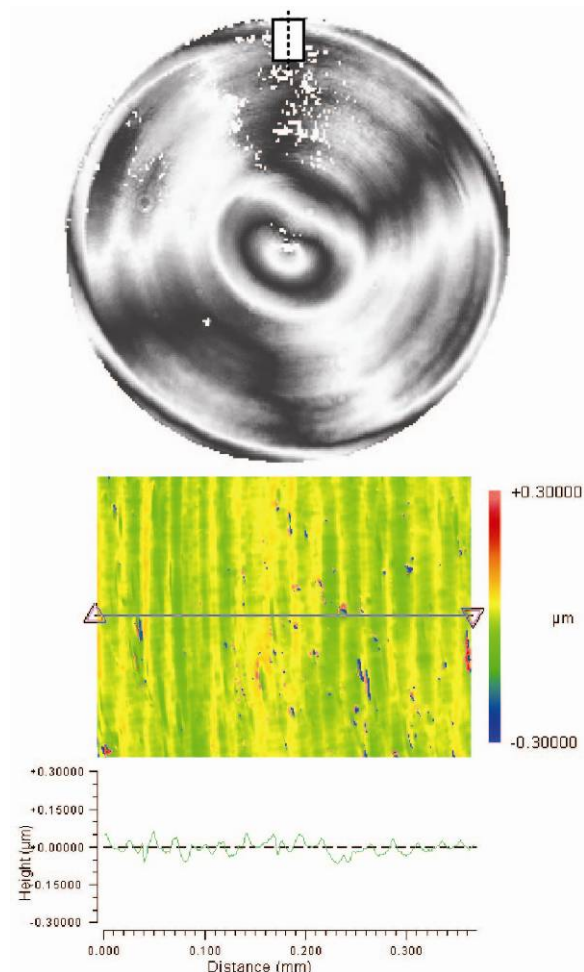
FIGURE 11. Data dropout in the interferograms of the lenslets produced with the Heidenhain 6000 encoder shows that C-axis encoder quality plays a major role in surface quality.



The waviness at the 12 o'clock position of the lenslet produced 90mm off-axis with the Heidenhain 6000 line encoder is shown in Figure 12. The trace through the middle of the data shows an average wavelength of approximately  $60\mu\text{m}$  and an average peak-to-valley of  $400\text{nm}$ . By comparison, Figure 13 shows the same measurement on the lenslet produced with Renishaw 16200 line encoder, except the average wavelength of the trace is about  $20\mu\text{m}$  (3x improvement) and the average peak-to-valley is about  $50\text{nm}$  (8x improvement). Based on the relatively low waviness and lack of data dropout on the lenslets produced by the Renishaw 16200, the practical work envelope could be 100mm to 200mm in diameter depending on finish requirements.



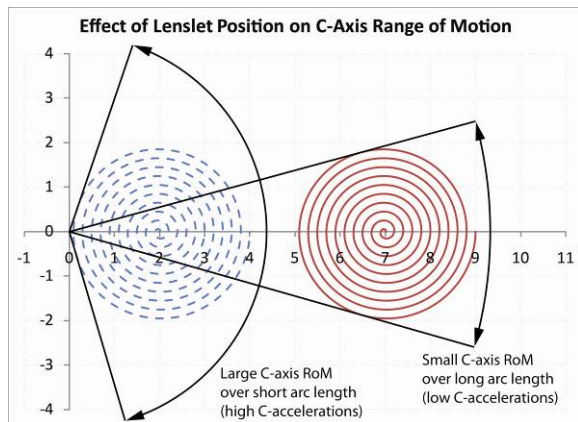
**FIGURE 12.** Waviness at the top edge of the lenslet produced 90mm off-axis with the Heidenhain 6000 line encoder. Wavelength  $\approx 60\mu\text{m}$ . P-V  $\approx 400\text{nm}$ .



**FIGURE 13.** Waviness at the top edge of the lenslet produced 90mm off-axis with the Renishaw 16200 line encoder. Wavelength  $\approx 20\mu\text{m}$ . P-V  $\approx 50\text{nm}$ .

Another consideration for the practical work envelope in X-C-Z machining is the proximity of the toolpath to the work spindle centerline. A straight line toolpath that passes just off center will require near infinite C-axis acceleration to make the  $\sim 180^\circ$  shift as the path goes from one side of the axis to the other. This results in large-scale CFE (though at a small radial distance). The CFE may be large enough to exceed limitations of the control and cause the machine to crash. Lens arrays with near-axis lenslets should be tested for C-axis accelerations to avoid crashing during an actual cut. Figure 14 shows an example of two lenslets at different off-axis locations. The near-axis lenslet will have a large change in C-axis motion over a relative small toolpath length. The other lenslet will have much less C-axis motion and will not pose a CFE problem. In practice,

proximity to the centerline is a minor issue for lens arrays that is solved with a slower feedrate when necessary.



**FIGURE 14.** *Lenslets close to the C-axis centerline will require high C-axis accelerations.*

## SUMMARY

By understanding toolpath programming, tool center errors, and practical work envelope, X-C-Z micromilling is a viable option for the manufacture of ultra-precision freeform and arrayed components. It has been in use by II-VI [1], Precitech, and other groups such as Fraunhofer IOF [2] for several years. At II-VI we have successfully produced micromilled lens arrays and freeform lens molds for customers in standard materials like copper and electroless nickel but also in crystalline materials including ZnSe and germanium. In practice, we can achieve positioning errors within  $\pm 1\mu\text{m}$  and figure errors approaching 0.5fr at HeNe with careful effort and freeform corrections.

## REFERENCES

- [1] Davis G, Roblee J, Hedges A. Comparison of Freeform Manufacturing Techniques in the Production of Monolithic Lens Arrays. Proceedings of SPIE. 2009; 7426, 742605.
- [2] Scheiding S, Gebhardt A, Eberhardt R, Tünnermann A. Micro Lens Array Milling on Large Wafers. Optik & Photonik. 2009; 4: 41-45.

# FEEDBACK OF MEASUREMENT DATA FOR CORRECTIVE MACHINING OF FREEFORM SURFACES

Christian Brecher<sup>1</sup>, Christian Wenzel<sup>1</sup>, Christian Buß<sup>1</sup>, Jürgen Clemens<sup>1</sup>  
<sup>1</sup>Fraunhofer Institute for Production Technology  
Aachen, Germany

## INTRODUCTION

The manufacture of aspherical molds and freeform surfaces is well established in the industry. Freeform mirrors and molds have reportedly been manufactured to accuracies in the submicron range [1]. However, once such molds are used for replication processes (e. g. injection molding) the produced lenses show process dependent defects, mainly shrinkage [2, 3]. Currently, the occurring shrinkage cannot be predicted with sufficient accuracy, hence the form of the mold has to be corrected iteratively to adjust the optical function of the lens [4].

Often, the shrinkage will occur in several confined regions of the lens and will be of inhomogeneous nature. Current models for shrinkage cannot predict the local and process dependent shrinkage, instead experiments have to be carried out, then shrinkage can be modeled for similar process parameters [5]. As a result conventional 2-dimensional measurements are not sufficient to identify local phenomena. Instead, the surface is often scanned on a measurement machine or interferometers with computer generated holograms have to be used. The measurement data for complex surfaces often consists of hundreds of thousands single points. This point cloud contains the information about the form and waviness errors of the surface. Also, the data contains stochastically distributed noise within the measurement uncertainty [6]. Multiple measurements are needed to distinguish between the repeatable surface error and a smaller statistical form error due to process instabilities.

The degradation of the optical function of an element cannot be calculated from a single measurement value, because the spatial frequency profile of the surface form error must be taken into account. The biggest contribution to the total optical error is a result of high-frequency form errors [7]. Additionally, surface roughness (highest spatial frequency) must be considered, which cannot be compensated by corrective machining. In effect, a band-pass filter

is needed to compensate only those mid-frequency form errors that have an effect on the optical function. Spatial parameters for this filter have to be carefully selected.

The principal method for shrinkage compensation by mold retooling for NURBS described free form optics has been laid out in [4]. There, the deviation map was converted into a NURBS surface and merged with the original design surface. The general idea for a compensation workflow has been shown to work. More precisely, the following steps have been carried out.

## Shrinkage Compensation Chain

- Measure mold insert and compare deviations against target geometry.
- Find optimal process point for stable replication results.
- Measure polymer optics multiple times and compare systematic and statistical deviations against mold and target geometry.
- Calculate new design geometry that incorporates the negative deviation found after the first replication step.
- Replicate again with the same process parameters.
- Measure again and calculate form deviations against target geometry.
- Repeat until target accuracy is reached.

In practice, only few retooling steps will be carried out, since measurement uncertainties and statistical process variations will counteract with an improved surface accuracy as shown in figure 1. This is not only a result of the concept of iterative machining but also a result of the choice of data processing.

Novel data filtering methods and a focus on correcting optical imperfections instead of form imperfections lead to better results for shrinkage compensation. We present a method using radial basis functions (RBF) to express the measured deviations and correct the original surface without leaving the data format of the original surface.

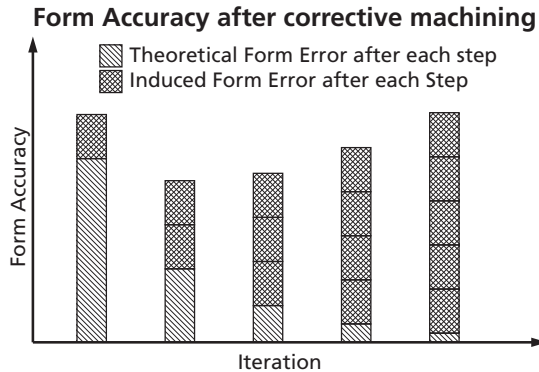


FIGURE 1. With each step in the cycle of corrective machining, the form accuracy is improved. For illustration purposes it is assumed to be reduced by 50% in each step. On the other hand measurement uncertainties as well as process imperfections during mold making and statistical errors during replication are introduced with each step. As a practical result the total form error increases after some cycles.

#### APPROXIMATION WITH RBF

Interpolation or more general approximation with RBF has been discussed in the field of computer graphics as well as in multivariate approximation theory [8, 9]. Since RBF approximation does not force a fixed grid of approximation centers, they are suited to model local effects on the discussed surfaces.

A radial basis function (RBF) is a real-valued function  $f$  whose value depends only on the distance from a center  $c$ , so that

$$f(x, c) = f(\|x - c\|),$$

where the norm is the Euclidean distance. A network of RBF, called radial basis function network (RBFN) is the linear combination of multiple RBF. Usually, the abbreviation RBF will refer not only to the single function but also to the network as a whole.

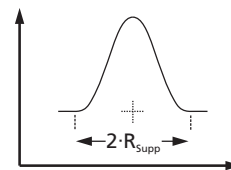
The choice of the RBF is important for the quality of the approximation in multiple ways. For practical considerations, especially the possibility to calculate the approximation within reasonable time is demanding. The classical example of a simple Gaussian function

$f(x, c) = e^{-\|x - c\|^2}$  for example is not suited for this problem because of its infinite support radius. As a result, the calculation of a point on the function network requires the evaluation of every function of the linear combination. Therefore compactly supported radius functions, e. g. Wendland's function [10], are usually used

for mesh free surface approximation. The compact support radius of a radial basis function leads to a strictly positive definite and sparse linear system that must be solved to find the approximation to the measured data [11]. Depending on the number of centers, this calculation can be carried out on a standard computer.

Another property of the support radius is explained in figure 2. It shows the high-pass and low-pass effect of the choice of support radius. In the former case, scattered data can be interpolated exactly, but the resulting reconstructed surface is meaningless for the mold compensation and would only introduce severe optical errors. The latter case approximates over a range of multiple measurement points with the effect of smoothing the data. Finding a good value for the support radius of the used RBF is crucial for the compensation of optical molds.

#### Radial Basis Function Network - RBFN



#### Features (adjustable)

Local Centre Density  
Compact Support Radius  
C2-continuous

#### Support Radius

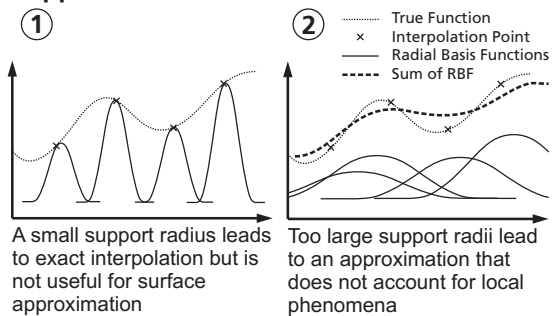
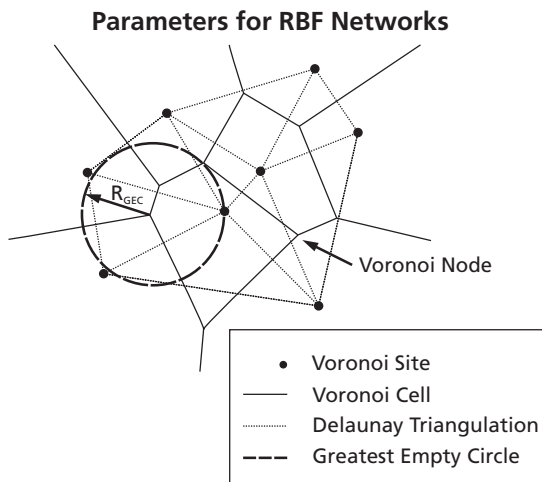


FIGURE 2. Radial basis functions can be chosen such that the resulting network of radial basis function is C2-continuous. The choice of the support radii is important for the filtering of the optical function of the compensated surface as well as for the manufacture of the surface.

Preprocessing of the measurement data is carried out to find a good estimate for the support radius of the RBF. One measure that gives a lower bound on the useful radius is the greatest empty circle that can be drawn within the complex hull of the measurement data. In order to find this radius, Voronoi tessellation is



employed. The centers of the function network are chosen adaptively until the necessary target accuracy is reached. It was found that the total number of functions is about two orders of magnitude smaller than the total amount of measurement points.



**FIGURE 3.** Voronoi tessellation is used to find the greatest empty circle that can be drawn within the complex hull of the scattered data set. In practice, values of  $R_{Supp} = 4-10 R_{GEC}$  have proven to be useful.

#### Data Feedback

Since optical surfaces are usually not given as RBF, a method has to be found to merge the original surface and the deviation map. For the simple case of a free form surfaces with low curvature, a NC program was written in Matlab.

#### RESULTS

First results have been obtained by applying the aforementioned methods to surfaces of optical components. Local shrinkage compensation by a factor of 3 could be achieved with a standard injection molding process. Further research will be focused on the investigation of single properties of the radial basis function approximation.

#### ACKNOWLEDGEMENTS

This research and development project is funded by the German Federal Ministry of Education and Research (BMBF) within the Framework Concept "Research for Tomorrow's Production" and managed by the Project Management Agency Karlsruhe (PTKA). The author is responsible for the contents of this publication.

#### REFERENCES

- [1] Steinkopf, R. et al. Metal mirrors with excellent figure and roughness. Bellingham, WA: SPIE, 2008 (SPIE Proceedings Series 7102)
- [2] Forster, Jan. Comparison of the optical performance of injection molded and compression injection molded plastic lenses, Dissertation RWTH, Verlag Mainz, 2006
- [3] Jansen, K., Van Dijk, D., Husselmann, M. Effect of processing conditions on shrinkage in injection molding. Polymer Engineering & Science, Volume 38, Issue 5, p. 838 – 846, 1998
- [4] Brecher, C., Buß, C., et al. Metrology data feedback for shrinkage compensated polymer lenses. Bedford: Euspen, 2009, Proceedings. Volume 2, p. 443 - 446
- [5] Kennedy, P. K., Zheng, R. Shrinkage of Injection Molded Material, Precision Injection Molding, Carl Hanser Verlag, Munich 2006, p. 105 – 135
- [6] Henselmann, R., Non-contact Measurement Machine for Freeform Optics, Eindhoven, Technische Universiteit Eindhoven, 2009, Proefschrift, p. 247 – 256
- [7] Ries, H., Timinger, A., Toleranzierung von Freiformflächen, DGaO-Proceedings 2007, ISSN 1614-8436
- [8] Y. Ohtake, A. G. Belyaev, and H.-P. Seidel. A multi-scale approach to 3D scattered data interpolation with compactly supported basis functions. In Shape Modeling International 2003, p. 153–161, Seoul, Korea, May 2003
- [9] Schaback, R., Reconstruction of Multivariate Functions from Scattered Data, Lecture Notes, Göttingen, 1997
- [10] Wendland, H., Scattered Data Approximation, Cambridge Monographs on Applied and Computational Mathematics, Cambridge University Press, 2004
- [11] Wendland, H., Computational Aspects of Radial Basis Function Approximation, in : Topics in Multivariate Approximation and Interpolation, K. Jetterer et al., Elsevier B.V., 2006
- [12] Floater M.S., Iske A., Multistep scattered data interpolation using compactly supported radial basis functions, J. Comput. Appl. Math, 8 : pp. 381-399, 1998



# MICROMILLING OF BIONIC STRUCTURES

Dirk Biermann<sup>1</sup>, Eugen Krebs<sup>1</sup>, and Juliane Schlenker<sup>1</sup>

<sup>1</sup>Institute of Machining Technology

TU Dortmund

Baroper Str. 301, D-44227, Dortmund, Germany

## ABSTRACT

For the improvement or influencing of the material flow and to reduce the tool wear in the sheet-bulk metal forming processes bionic microstructures are milled and coated on the functional surfaces. To achieve the desired shape with some sharp edges micromilling has been proved to be appropriate. However, the hardness required of the forming tools and the process-related requirements of the manufacturing process are the challenge and have to be academically examined. This paper presents first results from current experimental investigation of the micromilling of hardened steel. First, the machinability of hardened steel (cold-work steel X153CrMoV12 and high-speed steel HS6-5-2C) with commercially available cemented-carbide tools is tested for different cutting parameters like cutting speed  $v_c$ , cutting depth  $a_p$  and feed speed  $v_f$ . Furthermore, the paper presents the manufacturing of three different bionic structures from beetles, for which tools with a diameter  $d = 0.2$  mm, and focuses on explaining the milling strategies and the specific demands of each type of structure.

## INTRODUCTION

Today the development of new products is determined by rising complexity in product design and functionality. To meet these demands, innovative possibilities must be also investigated in manufacturing in the product development and in the process design. Application of a structure on a workpiece surface is one of many possibilities [1, 2]. Besides, a structure on the functional surface influences the frictional behavior between two components [3]. The choice of the type of the structure can be made supported by technological studies and simulations. For this purpose, the knowledge of additionally parameters such as material specifications and methods of use is necessary. Alternatively, structures been presented in nature can be also chosen. Because of evolutionary process the structures are optimized and absolutely perfect adjusted to their surroundings.

Especially in insects a lot of interesting structural patterns can be found on their shell.

In the Transregional Research Centre (TR) 73 sheet-bulk metal forming has to be researched. Thereby, in the development of dies which are needed for sheet-bulk metal forming the potential for improvement within process by using structured surfaces has to be examined. However, the structuring of the tool surface is a huge demand on the machining technology. Firstly, because the micromilling process, which requires small tool diameters, of hardened steel (up to 63 HRC) has not been adequately examined until now [4, 5, 6]. In addition, down scaling of the process parameters from the macro level, which has already been examined extensively, is limited [7, 8]. However, current investigations at Institute of Machining Technology (ISF) show positive results, and qualify the micromilling as a suitable method for the requirements [9].

In this essay the manufacturing of three different structures is described. To structure the surface with design of beetles means to manufacture very small pattern in a high precision. In this case high precision means to keep a consistent pattern over the defined surface, in which the dimensions of each element must be observed. Micromilling can meet these requirements, but need an in-depth understanding of the process. It is a matter of thinking that the manufacturing process of such structures is subjected to a high acceleration and deceleration rate, which is a high dynamic load to the milling machine especially to the drive axes. In addition, the small cross sections of the micromilling cutters mean a low stiffness, which increase a problematic tool drift and the risk of tool breakage. The consequences are shape and dimensional errors or reduced process stability. Therefore, before manufacturing the structures fundamental investigations are necessary to acquire a new knowledge first.

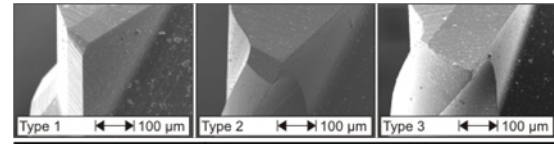
From the results of the fundamental investigation evaluation of suitable cutting parameters is described. In addition, results of the comparison test with micro cutters are presented. Furthermore, the bionic structures are illustrated with the focus on the manufacturing of these structures. At this point, the secondary optimization, which has been developed during the production process itself, is proven by SEM micrographs and white-light microscope measurements.

## FUNDAMENTAL INVESTIGATION

Within the fundamental investigation first and foremost the machinability of a hardened, carbide-rich cold-work tool steel 1.2379 (X153CrMoV12, 62 HRC) and a high-speed tool steel 1.3343 (HS6-5-2C, 63 HRC) with coated micro end-milling cutters is verified. In this assay some results of this experimental investigation are delineate. Beyond that the discussion elaborates on the determination of the cutting-parameter set, which enables an economic manufacturing of dies, the analysis of process forces and the surface quality. Complemented to this results the evaluation of the applicability of different tool types is validated by analyzing the process forces, the tool wear, the surface quality, the material removal rate  $Q_w$ , and the entire chip volume  $Q$ .

### Experimental Setup

The experiments were carried out on a micromachining center, KERN HSPC 2522. The spindle used, SC 1060-OA, has an operating range from  $50,000 \text{ min}^{-1}$  to  $160,000 \text{ min}^{-1}$ . The investigations were performed by down milling with different types of micro end-milling cutters with a diameter of  $d = 1 \text{ mm}$  and  $d = 0.3 \text{ mm}$ . As a cutting fluid supply system, minimum quantity lubrication (MQL) was chosen. The specifications of the tools ( $d = 1 \text{ mm}$ ) are listed and the cutting edges are illustrated in Fig. 1. The forces were measured with a 3-component dynamometer, Kistler MiniDyn 9256C1, and were recorded with a sampling rate of  $f_s = 50 \text{ kHz}$ . The used workpieces had a dimension of  $30 \times 40 \times 10 \text{ mm}^3$ . Each cutting-parameter combination was analyzed after a tool life travel path of  $L_t = 1.5 \text{ m}$ . The generated surfaces and used cutting edges of the tools were analyzed with the aid of a confocal white-light microscope, Nanofocus  $\mu\text{surf}$ , and a scanning electron microscope (SEM), Philips XL40 ESEM. Furthermore, the maximum width of flank wear land  $VB_{\max}$  was measured by light microscopy using a Mitutoyo MF-B 1720 H microscope.



| Type                      | 1                       | 2                       | 3                       |
|---------------------------|-------------------------|-------------------------|-------------------------|
| Coating                   | TiAlN                   | AlTiN                   | TiAlN                   |
| Tool length $l_t$         | 40 mm                   | 50 mm                   | 45 mm                   |
| Shank diameter            | 3 mm                    | 3 mm                    | 3 mm                    |
| Number of teeth $z$       | 2                       | 2                       | 2                       |
| Diameter $d$              | 1 mm                    | 1 mm                    | 1 mm                    |
| Ratio $l/d$               | 0.5                     | 1                       | 2.5                     |
| Helix angle $\varphi$     | $0^\circ$               | $25^\circ$              | $30^\circ$              |
| Rake angle $\gamma$       | $0^\circ$               | $10^\circ$              | -                       |
| Corner radius $r_q$       | 0.05 mm                 | $45^\circ$ chamfer      | 0 mm                    |
| Cutting edge radius $r_g$ | approx. $6 \mu\text{m}$ | approx. $6 \mu\text{m}$ | approx. $7 \mu\text{m}$ |

FIGURE 1. SEM micrographs of the cutting edges and specifications of the fine-grain cemented carbide tools.

## Results

To achieve suitable cutting-parameter set experiments with varying parameters were carried out. Thereby, design of experiments was used to reduce the number of experiments significantly. One of the most important analysis criteria is the evaluation of the process forces. Figure 2 shows the models of the averaged active and passive forces for the analysis of the interactions between depth of cut and feed per tooth as well as between width of cut and depth of cut (coefficient of determination  $R^2_{\text{adj}} = 0.972$  (active) and  $R^2_{\text{adj}} = 0.436$  (passive)). The models indicate a significant influence of the depth of cut on the active forces, because of the correlation between the depth of cut and the width of undeformed chip. It is noticeable that the width of the cut and the feed per tooth have a lower influence on the active force excepting the range of large depth of cut. The developing of the passive force clarifies that a reduction of the cross-section of undeformed chip leads to an increase of the passive force. This can be explained by the ploughing effect. Supported by means of the coefficient of determination of  $R^2_{\text{adj}} = 0.436$ , it is clear that the modeling of passive force for micromilling is very difficult because there are many disturbances which influences the micromilling process. Besides the investigation of the process forces the cutting-parameter set is determined by analyzing the tool wear and the generated surface. The comparison of the surface quality is characterized by the roughness profile  $S_a$  and the average surface roughness  $R_z$  of the last milling path. The burr height, measured at the

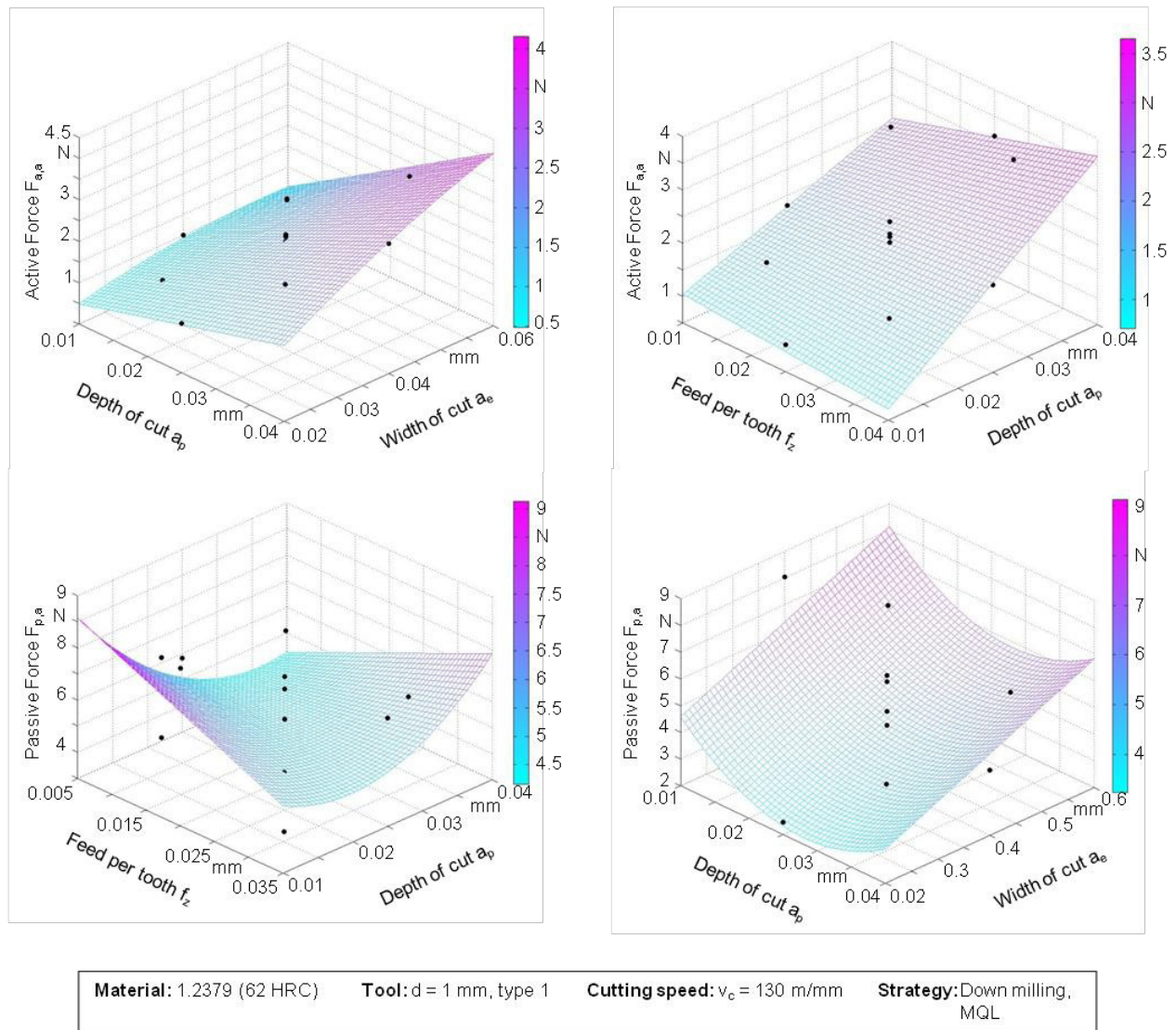


FIGURE 2. Models of the average forces for constant cutting speed  $v_c$  depending on depth of cut  $a_p$ , width of cut  $a_e$  and feed per tooth  $f_z$ .

flank of the last milling path, is a further criterion for the evaluation of the microstructure quality. The burr height, measured at the flank of the last milling path, is a further criterion for the evaluation of the microstructure quality. In addition, SEM micrographs of the workpiece surface are a qualitative evaluation criterion. Concerning the aim to machine as much chip volume as possible with one tool, the entire chip volumes  $Q$  is the main criterion. An additional criterion is the material removal rates  $Q_w$ . It achieves the following investigation results:

- $v_c = 130$  m/min
- $a_p = 0.025$  mm
- $f_z = 0.025$  mm
- $a_e = 0.6$  mm

To analyze further optimization potential, investigations with different tool types were carried out. Micromilling cutters with the same geometry are available with a diameter down to  $d = 0.2$  mm. The influence of tool type is assessed by means of process forces, the tool wear, the surface quality, the material removal rate, and the entire chip volume. Concerning the design of tools for the micromilling of presented difficult-to-machine materials, it is shown that cemented-carbide tools with robust cutting edges are most suitable. The best results were achieved with a tool, which has nonhelical cutting edges, a small corner radius, and a neutral rake angle. Due to the high stiffness, the minor tool length and the low aspect ratio, the applied forces lead to negligible tool deflections and vibrations. In



conclusion, test structures were produced successfully with the intention of validating the determined cutting-parameter set in combination with the selected tool types.

### MICROMILLING OF STRUCTURES

Based on the knowledge from fundamental research, simple and dependable manufacturing steps can be accomplished. Thanks to the understanding of interrelationships in the field of micromachining, this knowledge can be transferred to the production of more complicated form elements.

In the TR73 the structures of different insects were examined. In a selection process the scarab beetle (*scarabaeus sacer*) and the dung beetle (*Anoplotrupes stercorosus*) were considered to be suitable. Based on a detailed surface analysis, the structures of the beetle shell were designed and constructed in a CAD system. The two beetles and their structures are shown in Figure 3.

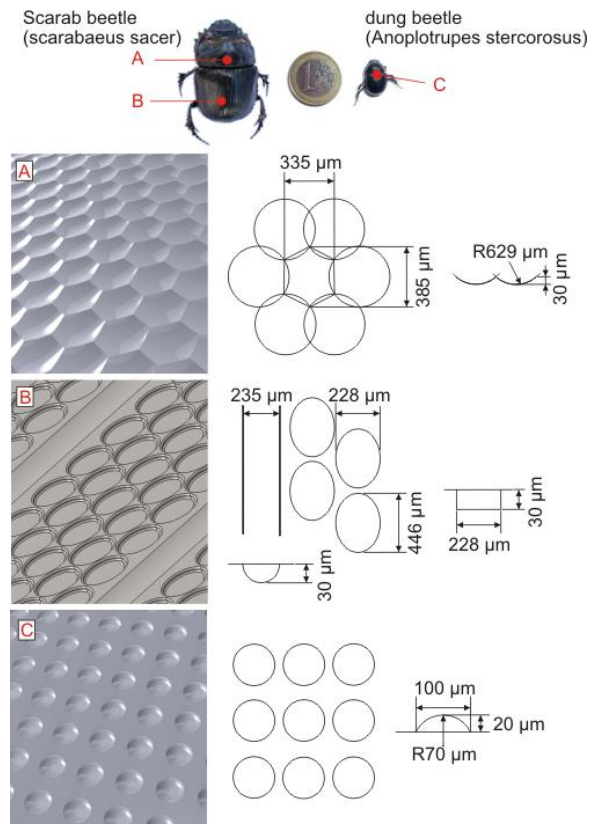


FIGURE 3. CAD models of bionic microstructures.

The first structure is located in the middle of the shell of the scarab beetle (Fig. 3). The structure form is a round cavity with six peaks. The second structure is found on top of the scarab

beetle's shell. This can be seen as a collection of oval cavities separated by parallel flutes. The dung beetle's structure has the smaller dimension. It is characterized by projecting hemispherical elements.

First, the CAD models are constructed for the cutting process (Fig. 4). Then, tool path calculations are carried out in a CAM system. After the milling (Fig. 4), the samples are coated by another member of the project and additional investigations of samples are carried out with respect to the quality of the coating or to the wear resistance.

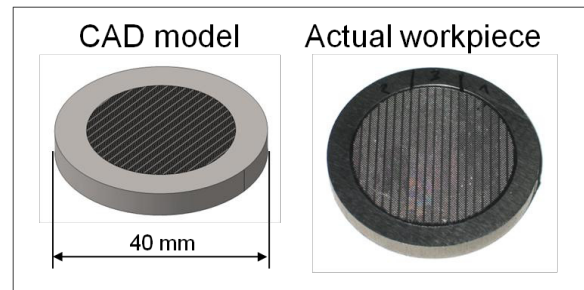


FIGURE 4. CAD model and workpiece with applied structure

In this essay only production of the samples using the micromilling process is described. The fundamental investigation provides the basis for the production of such structures. But some additional factors influencing the process are not examined in the fundamental investigation because of the simple process strategy employed there, yet they have to be considered. The small dimensions in the micrometer range and the large number of individual structural elements present an additional challenge.

Thus, rounded structural elements can only be made by using ball end mills. Such a cutter is appropriate for any free-form surfaces, but it also decreases material removal, compared with an end mill. In addition, a theoretical roughness profile is generated because of the ball geometry, which strongly depends on the width of the cut. It is important to keep in mind that in micromilling the roughness has a greater effect than in macromilling. Furthermore, the tool tip is engaged on the basis of a three-axis process. At the tool tip the cutting speed is nearly  $v_c \approx 0$  m/min. Therefore, it is no longer a cutting process, but becomes a pressing and squeezing of material, which deteriorates the quality of the surface. Moreover, it is not the actual tool diameter which is essential in the process but the effective radius which depends on width and

depth of cut. For the process this means that even higher rotational speeds are required, if the recommended cutting speed is to be adhered to. The speed range is limited though by the machine, or rather by the spindle. By using a main spindle with 160,000 rpm and a micro cutter with a diameter of  $d = 0.2$  mm, whereby the resulting effective radius during the process is  $r_{ef} = 0.05$  mm, the maximum cutting speed of  $v_c = 50$  m/min (recommended:  $v_c = 130$  m/min) can be achieved. In addition to the main spindle, the drive axes are also extremely stressed when such structures are produced. Continuous tool up-and-down movements combined with changes in the direction require not only high axis acceleration, but also a good positioning accuracy in order to achieve the shape and dimension precision needed. For the above mentioned case, the feed rate is  $v_f = 1600$  mm/min for a feed rate per tooth of  $f_z = 5$   $\mu$ m and a speed of  $n = 160.000$  1/min. However, in the milling process only an average feed rate of about 200 mm/min is possible, because of the limited process velocity results from the dynamics of the machine axis. The consequence is an actual feed per tooth below  $f_z = 0.5$   $\mu$ m. In this case, the chip thickness is not sufficient to ensure proper chipping, rather it comes to the ploughing effect. Pressing and squeezing of the material is based due to the fact that the cutting edge cannot be infinitely sharp and always contains a rounding on the cutting edge.

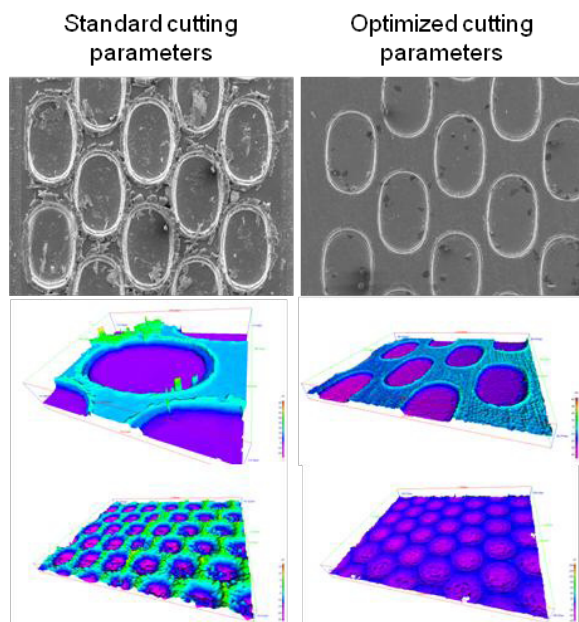


FIGURE 5. SEM micrographs (top) and white-light microscope images (bottom) of the produced bionic structure, milled with standard and optimized cutting parameters.

To counteract that effect, it is necessary, despite to the knowledge of fundamental investigations, to decrease the cutting speed so far that by regarding the dynamics of the machine an acceptable feed per tooth can be achieved. Experience has shown that for such small cutter diameters ( $d = 0.2$  mm) and the used cutting parameters ( $a_p = 15$   $\mu$ m,  $a_e = 10$   $\mu$ m) the lower limit for the feed per tooth  $f_z = 4$   $\mu$ m should not be exceeded. Figure 5 displays the improvement of surface quality and the reduction of burr formation which were achieved due to the adaption of this cutting parameter to the available machine tool.

## CONCLUSIONS AND OUTLOOK

For the production of bionic structures on hardened tool steel (1.2379 and 1.3343) fundamental investigations were carried out first. The experimental results presented in this essay show that an economic manufacturing of dies with cemented-carbide micro end-milling cutters is possible. Furthermore, cutting-parameter recommendations for a tool with a diameter  $d = 1$  mm can be made depending on the requirements. On analyzing different tool types good results were achieved concerning tool life travel path, material removal rate  $Q_w$ , entire chip volume  $Q$ , surface quality, and shape accuracy when using tool type 1, which has nonhelical cutting edges, a small corner radius and a neutral rake angle. Furthermore, the results show that the design of the tool is essential when micromilling steels with a hardness of more than 60 HRC. Using the results from the fundamental investigations further adjustments to the cutting parameters had to be undertaken because the dynamics and accuracy of the machine limit the milling of the bionic micro-structures. This milling of the structures enables a satisfactory surface quality to be achieved.

Nevertheless, it is important to exhaust all the possibilities that exist with respect to improving the process. Therefore, different tool inclination settings in feed and cross-feed direction will be investigated with the intention of applying this process to 5-axis micromilling of hardened tool steels and of avoiding cutting with the cutter center when using ball-end-milling cutters. In addition, integrating a milling simulation in the process is planned in order to carry out an intensive analysis of the undeformed chip.



## ACKNOWLEDGMENTS

This article is based on investigations of the Transregional Collaborative Research Center TR 73, which is kindly supported by the German Research Foundation (DFG).

## REFERENCES

- [1] Arntz K, Quito E F. Hartfräsen von Mikrostrukturen – zukunftsweisend für den Präzisionsformenbau. *Der Stahlformenbauer*. 2007; 6: 124-126.
- [2] Li P, Hoogstrate A M, Oosterling J A J, Langen H H, Munnig Schmidt R. Experimental validation of micro endmill design for hard milling application. *Proceedings of the 3rd International CIRP High Performance Cutting Conference*. June 12th-13th 2008, Dublin, pp. 69-78.
- [3] Brinksmeier E, Riemer O, Twardy S. Tribological behavior of micro structured surfaces for micro forming tools. *International Journal of Machine Tools & Manufacture*. 2010; 50: 425-430.
- [4] Klocke F, Arntz K, von Bodenhausen J. Potenzial beim Hartfräsen von Mikrostrukturen. *Mikroproduktion*. 2004; 1: 24-26.
- [5] Aramcharoen A, Mativenga P T. Size effect and tool geometry in micromilling of tool steel. *Precision Engineering*. 2009; 33(4): 402-407.
- [6] Aramcharoen A, Mativenga P T, Yang S, Cooke k E, Teer D G. Evaluation and selection of hard coatings for micro milling of hardened tool steel. *International Journal of Machine Tools and Manufacture*. 2008; 48(11/12): 1578-1584.
- [7] Kahnis P. Analyse von Größeneinflüssen bei einer Herabskalierung des Fräsprozesses in den Mikrobereich. *Dissertation*. Technische Universität Dortmund. 2008.
- [8] Klocke F, Bergs T, Veselovac D, Arntz K, Quito F J, Kratz S. Von der Makro- zur Mikrowelt. Herausforderung für den Mikroformenbau. *wt Werkstattstechnik online*. 2007; 97(11/12): 842-846.
- [9] Biermann D, Kahnis P. Mikrofräsen Filigraner Strukturen in Formeinsätzen. *MM Maschinenmarkt*. 2010; 5: 36-40.

# **MEASUREMENTS OF STRUCTURED SURFACES – CAN THEY BE MADE TRACEABLE?**

**Richard K. Leach and Claudiu Giusca**  
**National Physical Laboratory, Division of Engineering & Process Control**  
**Teddington, Middlesex TW11 0LW, United Kingdom**

The function of a component part can be profoundly affected by its surface topography. There are many examples in nature of surfaces that have a well-controlled topography to affect their function. Examples include the hydrophobic effect of the lotus leaf, the reduction of fluid drag due to the riblet structure of shark skin, the directional adhesion of the gecko foot and the angular sensitivity of the multi-faceted fly eye. Surface structuring is also being used extensively in modern manufacturing industry. In this way many properties can be altered, for example optical, tribological, biological and fluidic.

The measurement of surfaces has been carried out for over 100 years using a stylus instrument to trace a profile across the surface. Whereas a profile measurement may allow the investigation of process changes during manufacture, to gain an understanding of the functional nature of a structured surface, an areal measurement is usually required. For areal surface topography measurement a range of instruments, both tactile and optical, has been developed. However, a traceability infrastructure for areal surface topography measurements is not yet in place. This paper will discuss the philosophy behind such a traceability infrastructure and will describe the latest developments at the National Physical Laboratory, UK to develop primary instrumentation and calibration artefacts. The concept of a surface will be addressed from first principles and novel approaches to remove common systematic errors when using areal surface topography measuring instrumentation will be presented.

# MULTI-SCALE STRUCTURES FOR INFLUENCING THE TRIBOLOGICAL PROPERTIES OF METALLIC SURFACES

Reimund Neugebauer<sup>1,2</sup>, Andreas Schubert<sup>1,2</sup>, Miguel Avila<sup>1</sup> David Sylla<sup>1</sup>, Torsten Schmidt<sup>2</sup>

<sup>1</sup>Institute for Machine Tools and Production Processes  
TU Chemnitz  
09112 Chemnitz, Germany

<sup>2</sup>Department of Precision Technology and Micromanufacturing  
Fraunhofer Institute for Machine Tools and Forming Technology  
09126 Chemnitz, Germany

## INTRODUCTION

The surfaces of mechanical and precision components have a decisive influence on:

- tribological behavior
- dimensional precision of solid body contacts
- fatigue strength.

These important aspects are influenced, in turn, by the structure of the surfaces. The surface structures of solid bodies can be classified according to their characteristic feature size into meso, micro (e.g. roughness and waviness) and nanostructures.

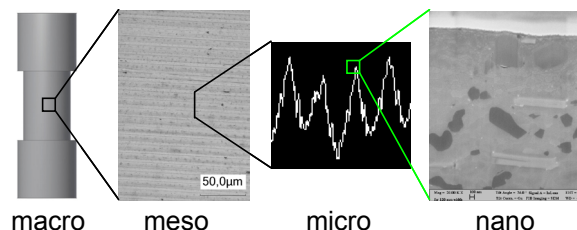


FIGURE 1. Overview of the various surface structure dimension scales.

To obtain desirable performance, whether it be higher wear resistance, lower friction, higher dimensional precision, or improved fatigue resistance, there's the opportunity to fabricate defined meso, micro or nanostructures on the surfaces. Meso and microstructures have been shown to improve the friction properties of lubricated gliding partners [1-3]. The structures act as pressure chambers and allow faster separation of the friction partners.

Also, nanostructures can have a positive influence on friction and wear. By suitable nanostructuring, the run-in condition can be generated prior to the service cycle. In this

manner, the wear-intensive run-in period can be minimized or prevented.

## REDUCTION OF TOOL WEAR BY SURFACE ENGINEERING

The influence of hardfacing on the wear resistance of hot forming tools has been investigated since several decades ago. Thick coatings of about 75 µm in thickness or greater have been shown to increase the wear resistance of hardened hot work steel in hot forging [4, 5]. However, hard coatings haven't found extensive usage in industrial hot forming because wear resistance improvements often do not make up for the high costs of coatings. Some studies have reported that surface treatments and small modifications of the alloying elements of hardened tool steel can actually provide higher wear resistance than hard coatings in critical areas of the tools [4, 6]. In the case of High-velocity Oxy Fuel (HVOF) thermal spray coatings, their poor adhesion to the substrate has limited their applicability in hot forging tools.

Surface preparation of the substrate prior to thermal spraying has an important influence on the development of coating-to-substrate adhesion strength. The state of the art consists of grit blasting to clean and roughen the substrate. Roughening creates the undercuts necessary for mechanical anchorage—generally regarded as the only relevant adhesion mechanism of thermal spray coatings. Sobolev et al. [7] proposed, however, that the constrain of thermal spray splat expansion upon impact imposed by surface asperities results in lower interfacial porosity and higher heat input into the substrate—two conditions that may increase adhesion strength. Yet, the variety of surface geometries and scales obtained from grit

blasting is quite limited for any attempts to adjust the incoming spray-substrate interaction—by design.

Surface structuring by laser ablation is a promising technology to manufacture deterministic structures on metallic substrates. Tailoring of substrate geometries with consideration of the thermal spray particle size and service conditions presents an opportunity to improve wear resistance of coating-substrate composites. In the case of thermally sprayed coatings on hot work steel surfaces, the potential benefits of deterministic substrate structures include:

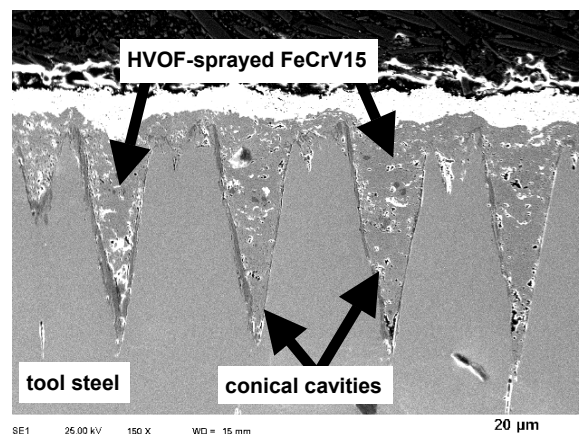
- Constrain thermal spray splat extension to promote diffusion bonding and reduce interfacial porosity
- Increase the coating-substrate interfacial area and thereby reduce interfacial residual stresses from coating deposition and from misfit thermal strains during hot forging temperature cycling
- Inhibit interfacial crack formation caused by cyclical loading of forging

To evaluate the feasibility of reaching the above goals, a pattern of conical cavities with a width of  $110\text{ }\mu\text{m}$  and a depth-to-width ratio of approximately 3:1 was manufactured by laser ablation on hardened hot work steel 1.2367. The tool steel surface had been previously ground to  $2\text{ }\mu\text{m}$   $R_z$ . A HVOF-thermal-spray duplex coating was deposited onto the textured and untextured areas of the substrate by first spraying an iron-based, hard alloy FeCrV15 powder followed by an WC-12% wt. Co top layer. The total thickness of the coating reached approx.  $100\text{ }\mu\text{m}$  from the ground surface. The surface structures were filled exclusively with the iron-based powder, having an average powder size of approx.  $50\text{ }\mu\text{m}$ .

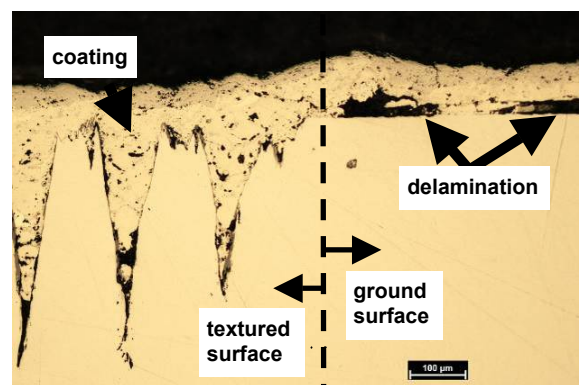
Figure 2 shows a cross-sectional view of the structured substrate after being thermally sprayed. The cavities were filled almost completely by the thermal spray coating (iron-based layer) with the exception of the sharp corners of the conical cavities in some instances. In this case, interfacial coating-substrate surface area well exceeds what would be achieved by grit blasting the hardened tool steel. In fact, peak-to-valley distances on a grit-blasted hardened steel surface would hardly

exceed  $10\text{ }\mu\text{m}$ . Figure 3 contrasts the coating adhesion developed on the structured surface vs. the adhesion on the ground surfaces. The coating delaminated completely off the ground surface immediately after the deposition process whilst it remained well-adhered to the laser-structured surface.

This initial evaluation confirmed that laser-machined structures of about twice the width of the average particle size of the deposited thermally-sprayed powder and a relatively high depth to width ratio (3:1) hold promise in increasing the adhesion strength of hardfacing coatings. Future work will focus on evaluating deterministic laser-machined structures with an array of geometry topologies and dimensions using metallographic characterization of the coating-substrate interfaces and tensile adhesion tests.



**FIGURE 2.** Scanning electron microscopy cross-sectional view of coating and laser-structured tool steel.



**FIGURE 3.** Cross-sectional optical micrograph of coating-laser structured tool steel composite.



## REDUCTION OF FRICTION BETWEEN LUBRICATED SURFACES

An optimization of tribological systems can improve the performance and lifetime of mechanical components. Surface structures have a substantial influence on the tribological behavior. Friction and wear coefficient can be reduced considerably by a specific change of the surface in the form of meso or microstructures.

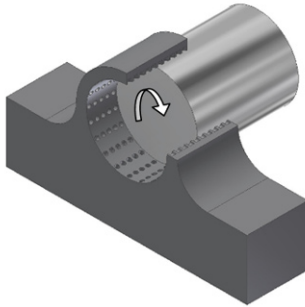


FIGURE 4. Shaft and microstructured bearing.

The goal of microstructuring of gliding partners can be represented by a shift of the Stribeck curve as shown in Figure 5. The Stribeck curve can be divided into the three regimes: boundary, mixed and hydrodynamic lubrication. First, a targeted surface structuring is intended to reduce the friction coefficient across the three regimes. Second, it would shift the curve toward the left, enabling to reach the hydrodynamic lubrication regime at lower operating velocities.

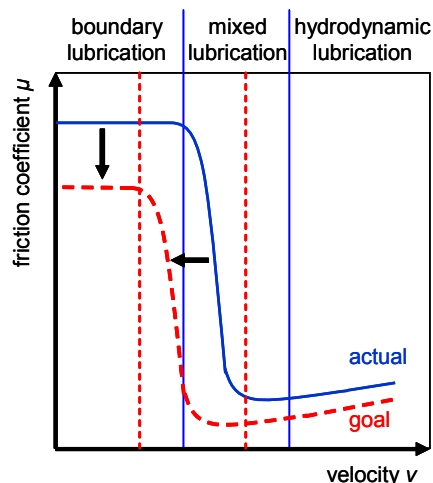


FIGURE 5. Desired effect on lubricated friction by means of structured surfaces.

A CFD simulation was performed to analyze the effect of surface microstructures on hydrodynamic lubrication. The simulation model consists of a lubrication gap between a static, structured base body and a smooth counter body which moves parallel to the former with a velocity of 1 m/s. For the purposes of this investigation, a spherical segment cavity was chosen. The simulation results showed that the cavity acts as a pressure chamber. The lubricant circulates in the structures (Figure 6) and consequently creates a pressure peak over the microstructure. This pressure would lead to faster separation of the lubricated solid bodies.

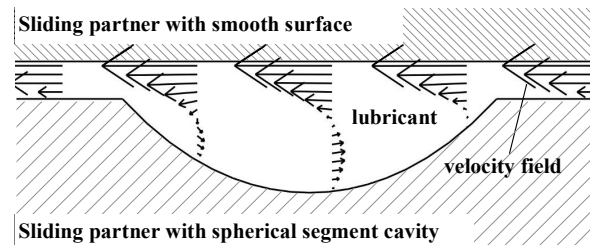


FIGURE 6. CFD simulation of lubricant circulation on a surface microstructure.

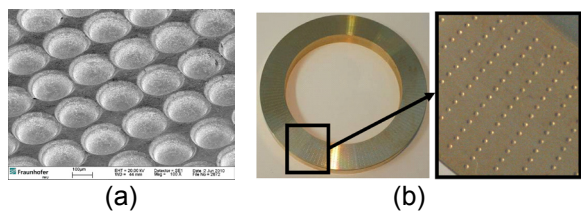
The following conclusions were drawn from the CFD simulations under hydrodynamic lubrication regime:

- with rising diameter, the pressure value increases almost linearly
- For maximum pressure, the depth of the structures should be between 5  $\mu\text{m}$  and 20  $\mu\text{m}$
- The distance between adjacent surface structures should be kept as small as possible to create maximum pressure.

The simulation results were verified experimentally by measuring the friction coefficient between lubricated, textured surfaces. To this end, a tribological ring-on-disc test rig was built. The ring partner was structured and the disc was flat-ground. The disc consisted of heat-treatable 42CrMo4 steel with an outer diameter of  $d_a = 100$  mm, a thickness of  $h_d = 8$  mm and a hardness of 650 HV. The ring-shaped counterbody was produced from bronze CuSn8 (hardness 125 HV) with outer diameter  $d_a = 100$  mm, inner diameter  $d_i = 70$  mm and thickness of  $h_r = 10$  mm.

Electrochemical Machining by closed-electrolytic-free Jet (Jet-ECM [8]) was used to produce patterned spherical segments. In Jet-ECM, a high-velocity electrolytic jet is generated from a cathodically polarized nozzle and led toward the anodically polarized workpiece. As positively charged ions are attracted to the nozzle, the negatively charged ions are attracted to the workpiece and material is removed as metal ions are drawn into the electrolytic solution. In contrast to conventional electrochemical machining, Jet-ECM enables localized material removal by control of jet position without relying on a solid electrode with the negative form of the feature to be machined.

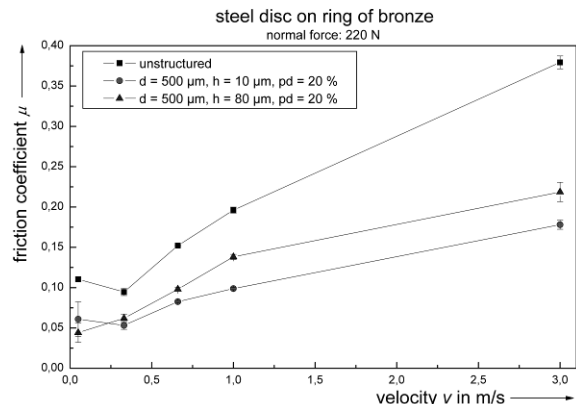
Initially, the electrochemical machining process parameters for the production of spherical-segment cavities were determined (Figure 7a). Afterwards, the cavities were machined on the ring samples (Figure 7b).



**FIGURE 7a.** SEM image of the microstructured surface; **7b.** spherical-segment cavities in a bronze ring ( $d = 500 \mu\text{m}$ ,  $h = 10 \mu\text{m}$ ).

Tribological measurements were carried out in a Wazau TRM 500 tribometer. The ring and disc were loaded with a normal force of 220 N and the disc was rotated with the following velocities: 0.05 m/s, 0.33 m/s, 0.66 m/s, 1 m/s and 3 m/s. The tests were conducted under immersion lubrication with engine oil Castrol EDGE 5W-30 at a temperature of 60 °C. The friction moment was measured to determine the friction coefficient. A ring-disc pair with smooth surfaces served as the reference condition.

An example result of the tribometric tests is shown in Figure 8. Here, the frictional behavior of the 42CrMo4 / CuSn8 pair with spherical-segment cavity depths of 10  $\mu\text{m}$  and 80  $\mu\text{m}$ , with a pattern density  $pd$  of 20 % (4080 cavities per ring), is plotted as a function of speed.



**FIGURE 8.** Comparison of the friction coefficient of an unstructured vs. a structured ring-on-disc for a pattern density  $pd = 20\%$ .

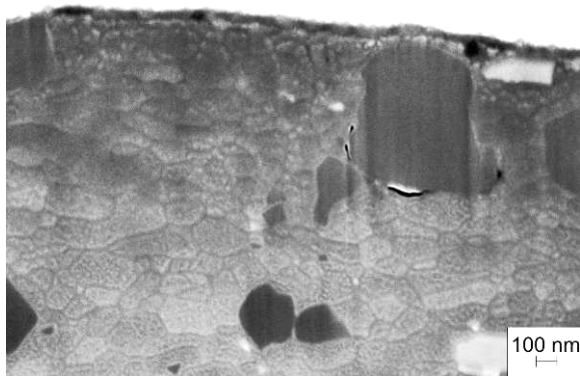
The unstructured pair showed a friction coefficient at the two smallest test velocities: 0.05 m/s and 0.33 m/s, of approx. 0.1. With a further increase of test velocity the friction coefficient rose nearly linearly and reached, at the maximum test velocity of 3 m/s, a maximum value of 0.37. The friction partners structured with spherical-segment cavities of 10  $\mu\text{m}$  and 80  $\mu\text{m}$  in depth maintained a lower friction coefficient than the unstructured partners over the complete speed range, with the exception of  $v = 0.05$  m/s. A reduction of the friction coefficient of up to 55 % was possible.

## NANOSTRUCTURED SURFACES BY FINISH MACHINING

Nanostructured surfaces can occur during the running-in phase of two friction partners. The running-in phase includes both mechanical and chemical effects. Peaks of roughness are leveled and a nanocrystalline structure is generated in the surface layer [9]. Furthermore, additives of lubricant and oil penetrate into the surface layer during the running-in phase and influence the frictional behavior. This nanostructured surface layer is known as the 'tribological mutation' or third body. The grain sizes of the primary alloy constituting a third body are smaller than 500 nm. The formation of these structures during the running-in phase depends of the material properties, the surface parameters and the load conditions of the friction partners. The third-body in the boundary layer leads to reduction of friction and reduce the wear rate. This effect should be utilizable for highly loaded systems. The objective is the reduction of the running-in time of highly loaded systems and generation of defined conditions for

layer formation. Hence, the energy efficiency would be improved in the early stages of service life. This can potentially be realized by inducing a nanocrystalline structure and a tribologically mutated surface with penetrated additives.

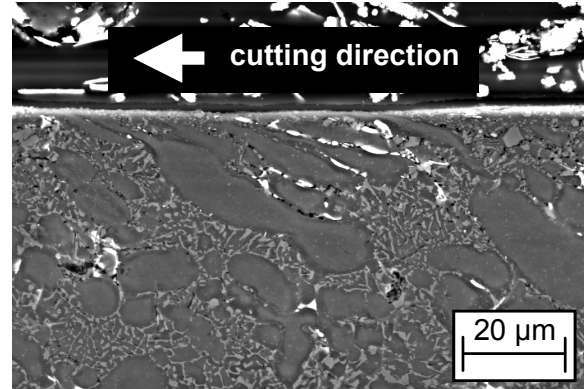
An example of a highly loaded system is a combustion engine. An important frictional interaction occurs between the cylinder liner and piston ring. In the present investigation, the material for finishing was a hypoeutectic AlSi alloy (AA 380.0). Focus centered on the machining of surfaces with nanostructures and chemical manipulation by turning. A further step was the development of nanostructures on a cylinder liner.



**FIGURE 9.** Nanostructured surface of a hypoeutectic AlSi alloy (AA 380.0) (FIB).

Different measurement methods were used for to evaluate the surface manipulation results. The Focused Ion Beam (FIB) method was used in order to analyze the structure of the surface layer. The key advantage of this procedure is the high disbanding and non-oxidization of the sample during analysis. Figure 9 shows a nanostructured surface of a hypoeutectic AlSi alloy finished by turning. The dark particles in this picture are silicon particles whereas the lighter grains are made of aluminum.

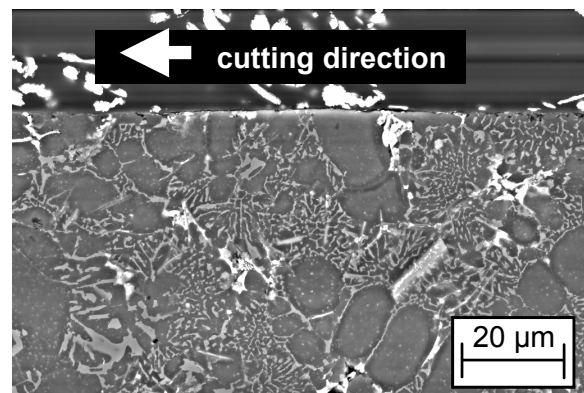
The present investigations on the turning process showed that the contribution of high shear stresses during cutting lead to the formation of a fine-grain surface layer. The high shear stresses were generated by comparatively high passive forces and modified cutting tool geometry. During generation of a fine-grained surface layer, passive forces of 6 N to 14 N were measured for this AlSi alloy.



**FIGURE 10.** Cross-section of an affected matrix.

Figure 10 presents the cross-section of an affected matrix after conducting a finishing process with high shear stresses. A characteristic effect of the high shear stress is the cross-section deformation in the cutting direction. Also, the destruction of the dendritic structure in the surface zone is an indication of finishing with high shear stress.

For comparison purposes, Figure 11 depicts an unaffected matrix. In this instance, there were no signs of grain refinement nor dendritic phases in the surface layer. During the finishing process for this unaffected matrix, passive forces of 1 N to 2 N for this AlSi alloy were measured [10].



**FIGURE 11.** Cross-section of an unaffected matrix.

## CONCLUSION

The performance and energy efficiency of engineering components is greatly influenced by their surface properties. This investigation showed that improvements in friction and wear behavior are possible by the manufacturing of

appropriate surface structures in the nano, micro and mesoscales.

It was determined that surface structures have the potential to improve the adhesion strength of thermal spray coatings on tool steel surfaces. These structures would enable thermal spray hard coatings to increase the wear resistance of hot forging tools.

The influence of surface structures on friction between lubricated sliding partners was investigated. CFD simulations of lubricated sliding partners indicated that surface microstructures act as micro-pressure chambers that lead to hydrodynamic lubrication regime at lower operating speeds. It was determined from lubricated ring-on-disc tests that surface microstructures may reduce friction by up to 55 %.

Nanostructures are formed during the highly energetic break-in period of sliding components and constitute the so-called "third body" This paper presented preliminary results on the generation of nanostructured surfaces for powertrain components with the purpose of reducing or eliminating the break-in period of sliding components such as cylinder liners.

It is possible to obtain further improvements in the tribological behavior of functional surfaces by simultaneously combining surface structures in the meso, micro and nanoscales. Such integration of multi-scale surface features should be the focus of future research.

## REFERENCES

- [1] Dumitru G, Romano V, Weber H P, Haefke H, Gerbig Y, Pflüger E. Lasermicro-structuring of steel surfaces for tribological applications. *Applied Physics*. 2000, A 70: 485–487.
- [2] Wan Y, Xiong D-S. The effect of laser surface texturing on frictional performance of face seal. *Journal of materials processing technology*. 2008, 197: 96–100.
- [3] Lu X, Khonsari M M. An experimental investigation of dimple effect on the Stribeck Curve of journal bearings. *Tribology Letters*. 2007, 27: 169–176.
- [4] Joost H-G. Beschichten von Schmiedegesenken. *Umformtechnisches Kolloquium Hannover, Hannoversches Forschungsinstitut f. Fertigungsfragen*. 1977, HFF-Bericht 9: 99–104.
- [5] Lodge K J, Still F A, Dennis J K, Jones D. The application of brush-plated cobalt alloy coatings to hot- and cold-work dies. *J. Mechanical Working Technology*. 1979, 3: 63–75.
- [6] Brockhaus HW, Guderjahn A, Schruff I. Improving the performance of forging tools - A case study. 6th International Tooling Conference. 2002.
- [7] Sobolev V V, Guilemany JM, Nutting J, Miquel J R. Development of substrate-coating adhesion in thermal spraying. *International Materials Review, ASM*. 1997, 42 (3): 117–136.
- [8] Hackert M, Meichsner G, Schubert A. Generating plane and microstructured surfaces applying Jet Electrochemical Machining. *Proceedings of Fifth International Symposium on Electrochemical Machining Technology, Fraunhofer IKTS Dresden, Editors: A. Michaelis, M. Schneider*. 2009.
- [9] Dienwiebel M, Pöhlmann K, Scherge M. Origin of the wear resistance of AISi cylinder bore surfaces: studies by surface analytical tools. *Tribology International*. 2007, 40: 1597–1602
- [10] Schubert A, Nestler A, Schmidt T, Schneider J. Finishing of aluminium based light weight materials – influence on surface properties. *Sustainable Production for Resource Efficiency and Ecomobility. International Chemnitz Manufacturing Colloquium*. 2010, 447–464.



# METROLOGY OF ASPHERIC AND FREEFORM LENSES BASED ON CONTOUR AND FORM

Andreas Beutler  
R & D  
Mahr GmbH  
Göttingen, Germany

## ABSTRACT

A new type of machine setup combining a profilometer with a rotational measuring axis to measure aspheric lenses is presented. The instrument is very flexible, as it does not need a specific hologram for each type of asphere. In general, the setup is also capable to measure freeforms. Metrology strategies and first results are presented.

## INTRODUCTION

Due to the increasing number of applications of aspheric and freeform lenses a lot of effort has been put into the refinement of the production process.

In the field of metrology for the production of aspheric lenses a few new setups have been shown recently [1]. One of the systems, a tactile 3D-system based on form and contour measurements, is presented.

Originally, the development of this tactile 3D-system started with the task to measure grinded surfaces. Polished surfaces are typically inspected with interferometers involving holograms or, more flexible, with stitching interferometers. Unfortunately, the interferometers can only measure on surfaces with sufficient reflectivity, i.e. on polished surfaces. In order to get any information of the grinded surfaces, a tactile profilometer is applied. Assuming that the aspheric lenses are rotational symmetric, one linear scan of the profilometer across the zenith of the lens should give a representative description of the shape including the defects.

Additional very time consuming linear scans on different angles may provide additional information. But this is hardly appropriate to create a real 3D image similar to the result of the interferometer.

Considering freeform surfaces, there are only very few and expensive high precision metrology systems available [2]. As there is usually no characteristic line across the surface describing the freeform it is necessary to measure the

complete topography. Thus profilometers collecting single scans can not be applied.

## METROLOGY SETUP

A new way to make a tactile measurement of the topography of an aspheric lens is to combine a rotational axis, which is capable to perform real measurements, with the profilometer (see FIGURE 1). This setup allows to take linear scans over the zenith and polar scans, which can be collected very fast, around the lens. A sufficient set of scans will then take a few minutes to record. An example of the distribution of the measured points is shown in FIGURE 2. In this way even data from “blind” grinded surfaces can be obtained and thus may be an additional tool to optimize the production of aspheric lenses.

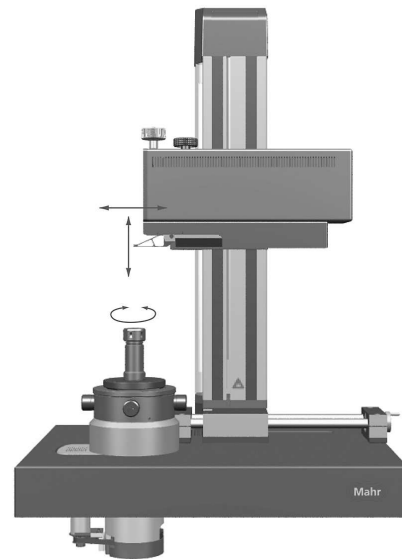


FIGURE 1. Measuring system combining a profilometer with a rotational measuring axis.

Another aspect of this new method is its flexibility. A hologram needed for each type of asphere is costly and has significant delivery times. With this tactile setup a new type of

asphere can easily be measured in a fast and inexpensive way. Depending on the demanded accuracy of the lenses the 3D tactile system can be used for the polishing process and the final inspection. This is of special interest for lenses, which are only produced in low quantities. In addition, the deviation of the asphere from a sphere is not limited as it is usually the case for interferometer setups. Thus even extreme aspheres and conical shapes can be measured.

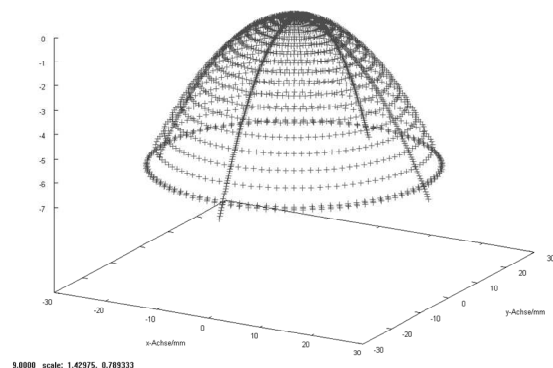


FIGURE 2. Measured points from linear and polar scans of an aspheric sample .

## RESULTS

First results on e.g. rather perfect samples such as calibration spheres have been presented before [3].

In FIGURE 3 is shown a study of the influence of the number of polar scans and filtering on the measuring results. The sample is an aspheric lens of about 50 mm diameter. The images in the first row show the differential topography obtained from measurements with 20 polar scans, in the second with 30 and in the bottom row with 40. The images in the first column show the results with no filtering, in the second column a median filter of 1 mm and in the third column a median filter of 2 mm is applied. The first row without any filtering shows that increasing the number of circles from 20 to 30 additional fine structure is detected, whereas increasing the number to 40 does not provide much additional information. The 10 additional polar scans just increase the measuring time. A median filter of 1 mm, which is in the range of the distance between the circles, does not change the structures much. However, applying this filter is recommended as very small Moiré-structures from the interpolation can be eliminated. Clearly visible is an influence of a 2 mm filter.

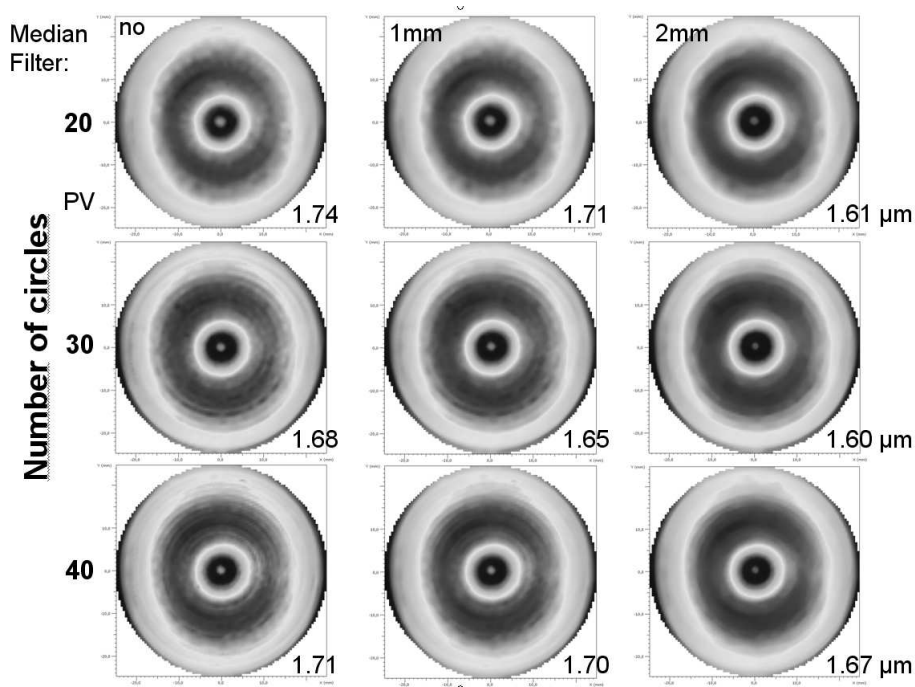


FIGURE 3. Measuring results of an aspheric lens with different number of polar scans and filters.

In contrast to most of the metrology systems available for aspheres, the setup presented should also be capable to measure freeforms. Freeforms may be classified describing their outer geometry, i.e. circular or e.g. rectangular, and the shape of the topography, i.e. off-center spheres and aspheres, toroids, cylinders and real freeforms.

As the instrumental setup is designed for rotational symmetric aspheric lenses, circular objects can be measured with the standard scanning paths over the surface. However, the instrument is capable to lift off the probe tip and contact again automatically. Thus even segments of circles and lines can be collected allowing to describe e.g. a rectangular geometry. In FIGURE 4 is demonstrated how the grid of scans can be distributed over a surface with rectangular outer geometry. In addition, adjustment marks for the freeform can be measured if they fit inside the measuring range (see FIGURE 4).

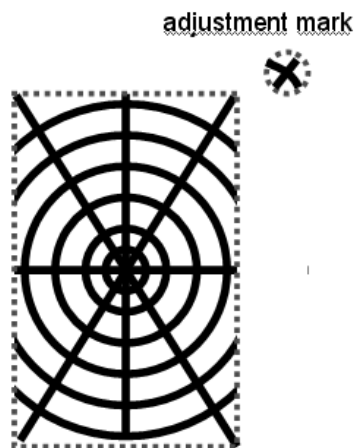


FIGURE 4. Grid of scans on a rectangular geometry.

FIGURE 5 shows a measurement of a sample with holes. In this case linear and polar scans consist of different segments. At the edge of a hole the probe tip is lifted off the sample, the sample is rotated (polar) or the probe moved (linear), the probe tip contacts again on the opposite edge of the hole and the measurement is continued. The complete process can be recorded on the sample and then automatically repeated on samples with the same geometry. Thus complex programming can be avoided.

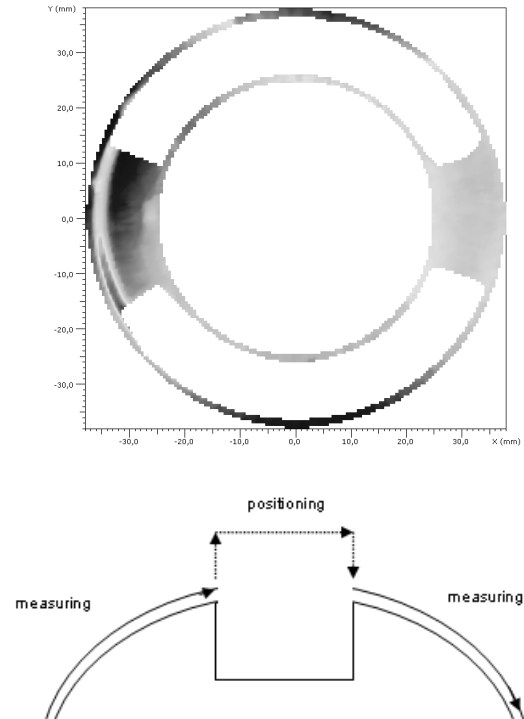


FIGURE 5. Measuring result and process of a sample with holes.

Comparing the measuring process of aspheres and freeforms, the major difference is found in the data processing: some simplifications due to the rotational symmetry of the aspheres can not be applied anymore for the non-rotational symmetric freeforms.

In order to determine the quality of the measuring process of freeforms, measurements are performed on rather simple structures such as spheres and aspheres. They can be measured as rotational symmetric objects if they are centered on the rotational measuring axis. By this very good reference data can be obtained, which is usually difficult to get for real freeforms, as there are not many instruments capable to measure real freeforms available. The samples can also be mounted off-centered on the rotational axis. In this situation, they can be considered as freeforms as they are not rotational symmetric anymore for the measuring process.

Another specific freeform is a toroid. An example of a measuring result is shown in FIGURE 6. In the measuring process first one polar scan is performed. An analysis of this scan allows to find the orientation of the toroid, i.e. the toroid can be rotated that the linear scans at 0° and

90° will represent the two radii (X and Y) of the toroid (see FIGURE 6: 0°/X and 90°/Y).

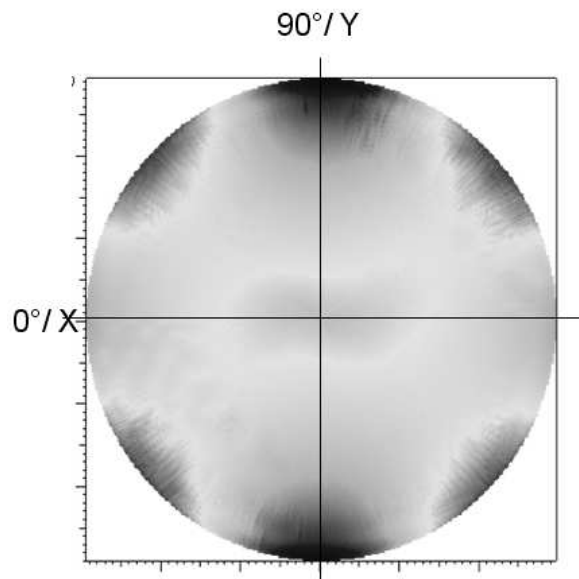


FIGURE 6. Measuring result of a toroid.

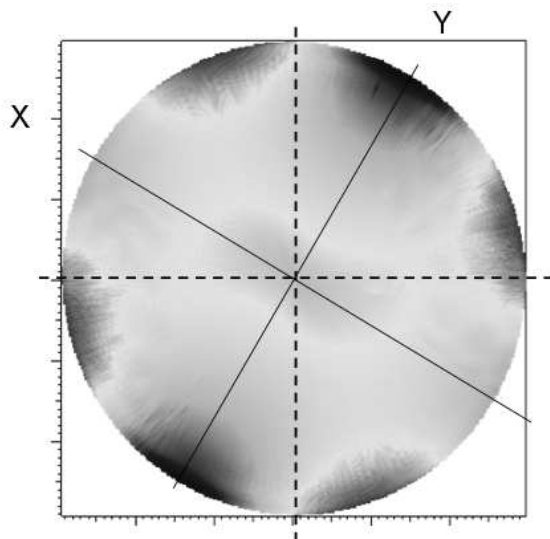


FIGURE 7. Measuring result of a toroid rotated in comparison to the measurement in FIGURE 6.

FIGURE 7 shows another measurement of the same sample but rotated by about 30° starting angle. The two linear scans do not anymore represent the two base radii of the toroid. In fact, they do not give any valuable information. However, the result of 3D-measurement is highly comparable to the result of the pre-oriented measurement (FIGURE 6). This

demonstrates that in this case a specific orientation of the sample for the 3D measurement is not necessary. It is a basic need for real freeform surfaces, where no specific structures for a specific orientation are available.

## SUMMARY

For the production process of aspheric and freeform lenses a new type of machine setup allows to measure the lenses in a very flexible way. It combines a profilometer with a rotational measuring axis. For aspheres results from measurements with varying parameters are shown. For freeforms the metrology strategy is described for different outer geometries. Measurements are performed on rather simple structures as off-axis spheres and aspheres and toroids. Considering the measuring process they can be considered as freeforms as they are not rotational symmetric.

## REFERENCES

- [1] Asphere Metrology on Joint Investigations, 4.High Level Expert Meeting 2010, UPOP, Braunschweig March 2010..
- [2] Ultra Precision Manufacturing of Aspheres and Freeforms, OptoNet Workshop, Jena Sept. 2010.
- [3] Beutler A, New metrology approach for the production of aspheric lenses. Aspherical Metrology, Technical Program, SPIE Optifab, Rochester NY May 2009.



# SURFACE FORM MEASUREMENTS COMBINING BEAM PROPAGATION, OPTICAL SCATTERING, AND PHOTOGRAMMETRY

Kevin E. Bowes<sup>1</sup>, Brigid Mullany<sup>1</sup>, Edward Morse<sup>1</sup>, and Angela Davies<sup>2</sup>

<sup>1</sup>Department of Mechanical Engineering and Engineering Science

<sup>2</sup>Department of Physics and Optical Science

University of North Carolina at Charlotte

Charlotte, NC, USA

## ABSTRACT

A technique has been developed where surface form measurements are obtained by combining photogrammetry and optical scattering as an alternative to conventional measurement. The method involves rastering a laser beam across the surface to be measured. At each laser location, the direction and orientation of the incident and reflect beams are determined using photogrammetry. This is done by taking photographs to capture the beam locations where they pass through two tinted windows (see Figure 1). These coordinates enable the calculation of the surface normal at each raster position. The surface normal at each position can then be integrated to arrive at the surface

profile. We have demonstrated the technique by measuring a profile of three different mirrors, estimating the radius of curvature and the sag for each, and comparing these values to the manufacturer specifications. The preliminary results show differences at the level of less than 4%. A significant contribution to the current measurement uncertainty is the coarse translation steps (2 mm) that are possible with the current set up. Developments are underway to fully automate the measurement, which will allow high resolution steps and an improved measurement. This measurement can be done in situ, is inexpensive, and can have a large dynamic range, enabling measurements of diverse free-form surfaces.

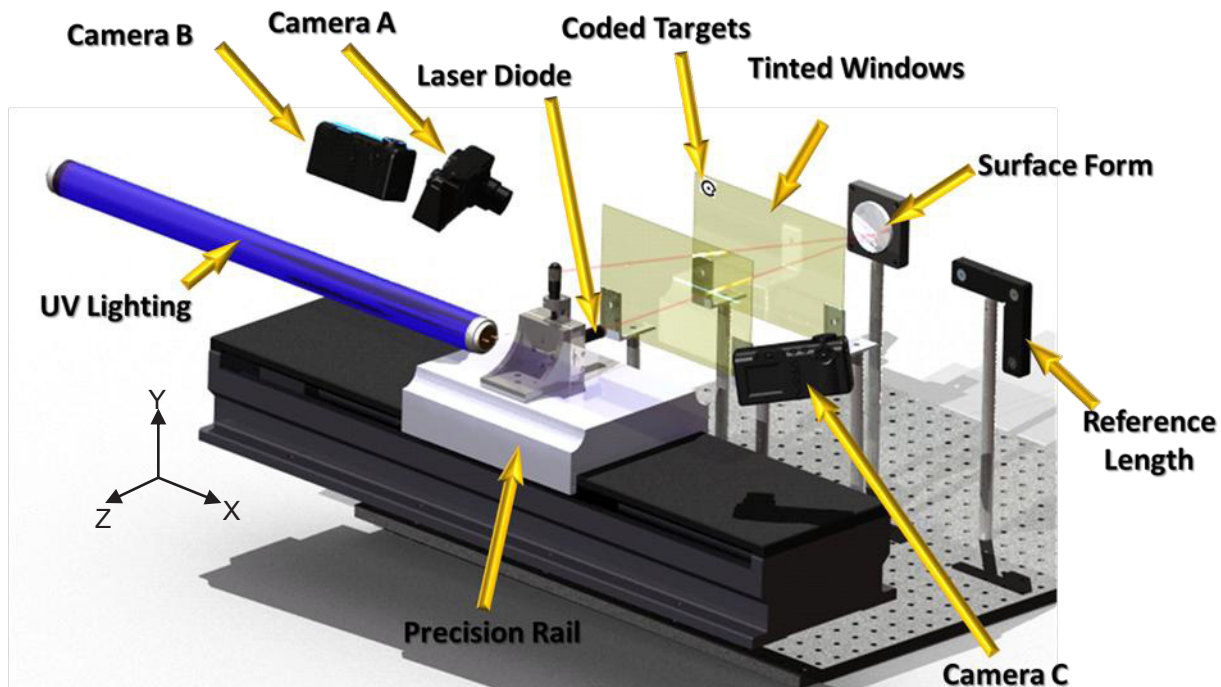


FIGURE 1. In-situ measurement setup for preliminary testing. The locations where the incident and reflected beams pass through the tinted windows is determined through photogrammetry, using the photographs taken by three cameras. These spot locations determine beam locations and orientations and therefore the surface slope on the part to be measured.

## INTRODUCTION

Ultra precision multi-axis diamond machining can be used to manufacture optical quality free-form components. Final inspection is not typically completed while the part is on the machine; rather the part is measured externally with a coordinate measuring machine (CMM), an optical scanner, or an interferometer. Contact measurements can compromise the surface quality, interferometry is best suited to nearly flat or spherical components, and common optical scanning techniques often do not meet desired measurement uncertainties. Further, removing the part for the measurement breaks the connection between the part and machine-tool coordinate systems and re-machining is difficult. In this study, we propose a new measurement that combines photogrammetry and optical scattering, with specular reflection of a laser beam from the part. A laser beam is directed toward the surface and reflected from the surface to be measured, passing through two tinted windows (see Figure 1). Photogrammetry is used to determine the absolute coordinates of the beam locations at the two windows, which is then used to define the incident and reflected beam orientations. Vector calculus is then applied to determine the surface normal, and finally the profile is extracted via integration. The proposed approach is low-cost, non-contact, in situ, and can measure arbitrary free-form surfaces.

### Principles of Photogrammetry

Scattering occurs as the beams pass through the tinted windows and this scattered light is easily observed as spots on the tinted windows. Photographs are taken of these spots from different orientations to allow a photogrammetry measurement of the spot coordinates. We begin with an overview of photogrammetry.

Photogrammetry entails taking multiple 2-D overlapping images of a 3-D object, and subsequently applying triangulation techniques to obtain the original 3-D form. This holds an advantage over theodolites, as photogrammetry can triangulate multiple points simultaneously. Figure 2 gives an example of multiple point triangulation. In order for a collection of points to be triangulated, the orientation of each camera, meaning camera position and aiming angle, must be calculated. This is typically accomplished in a process termed bundle adjustment. Bundle adjustment, carried out by photogrammetric software, simultaneously

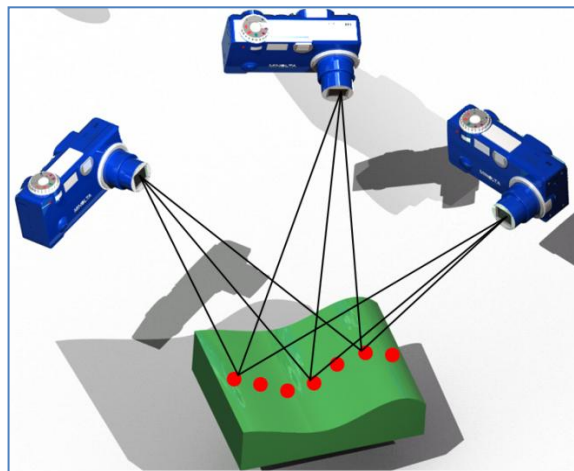


FIGURE 2. Multiple point triangulation

solves for the coordinates of a set of points and the camera orientations [1].

Notice in Figure 2 that multiple cameras are needed to carry out triangulation. A minimum of two overlapping images, taken from different locations and angles are needed to obtain enough information to reconstruct the 3-dimensional part being measured. Because more information is gathered with each additional camera location, a better approximation for the point coordinates,  $P_i (x_i, y_i, z_i)$ , can be obtained by increasing the number of images. It is also important for reliability and high accuracy results that the images are of high quality. High quality photographs suitable for photogrammetry depend not only on camera resolution, but also on the camera's format size, optimum camera orientations with respect to each other, an appropriate number of high contrast, common identification target visible in multiple images, and good camera calibration. If all of these factors are optimized, an accuracy of 1:30,000 is achievable [2,3].

Camera calibration is the process of resolving several optical characteristics including the charged-coupled device (CCD) format size, focal length of the lens, the principal point (where the optical axis of the photograph intersects the photograph), and several distortion parameters of the lens system. Photogrammetry can be used as an accurate measurement system provided that the cameras used have been properly calibrated [4].

Photogrammetry measurements are dimensionless and have arbitrary scale unless

there is at least one known distance specified in each photograph. The absolute distance between two points, called the reference length, must be known in order to scale measurements made via photogrammetry. The coordinate system in which the point locations are referenced is also typically defined with respect to this reference length.

### Experimental Setup

The setup is illustrated in Figure 1. A 40 mW red laser diode ( $\lambda = 650 \text{ nm}$ ) is mounted to a 12 mm translation stage micrometer such that the laser can be aligned along the Y-axis. The translation stage is mounted to a precision rail manufactured by TRIMOS Inc. of Switzerland. The precision rail has a resolution of  $1 \mu\text{m}$  and a translation range of approximately 1 meter. The laser is directed toward the surface form to be measured. Between the surface form and laser are two semi-transparent windows. The windows are  $127 \text{ mm} \times 203 \text{ mm} \times 2.286 \text{ mm}$ . They were manufactured from polycarbonate and made semi-transparent by lightly polishing the surface with a #600 grit sanding film on both sides. As a single beam is emitted from the laser diode, it passes through the semi-transparent windows where a footprint or spot is visible from the light diffusely scattering off each window. The beam is reflected off the specular surface being measured back through the same windows.

The setup also includes three Canon PowerShot SX110IS digital cameras arranged around the windows. The 9.0 megapixel resolution cameras are used to capture images of the four scattered spots on the two windows caused by the incident and reflected beams. The cameras are connected to a computer via a USB hub and can be programmed through a software package (PSRemote Multi-camera by Breeze Systems [5]) to simultaneously take images.

An illuminated reference length (Figure 3) was fabricated, because the beam scattered spots are best seen in low room lighting conditions. The reference length is three  $200 \mu\text{m}$  multimode fibers housed in an aluminum fixture. The dimensions of the frame as measured by a coordinate measuring machine (CMM) are  $96.5 \text{ mm} \times 96.5 \text{ mm} \times 12.7 \text{ mm}$ . The fibers connect to the body of the reference length and are arranged in an L-shape to provide a coordinate system. The opposite ends of the multimode fibers connect to a light source box (not shown) with three high intensity light-emitting diodes

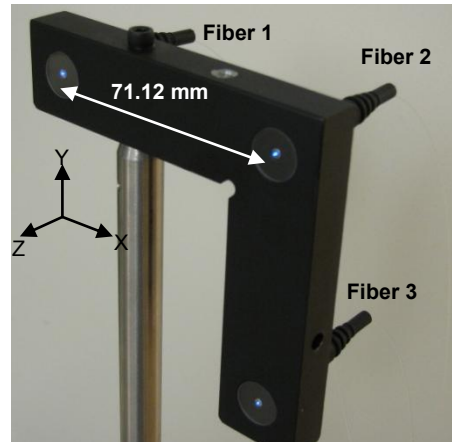


FIGURE 3. Reference length utilizing three  $200 \mu\text{m}$  multimode fibers and a blue LED source.

(LED). The LEDs are regulated by a potentiometer to enable optimum brightness control.

Fluorescent coded targets, examples of which are shown in Figure 4, are fixed to the semi-transparent windows. These targets are automatically identified and referenced to each other in multiple images by the photogrammetry software package (Photomodeler™ by Eos systems). Coded targets are used to initiate the automated process explained later under *Results and Discussion*. Once the locations of the coded targets are found, the estimated coordinates of all other spots generated on the window and from the reference length can be found and referenced accordingly. Figure 5 illustrates how points are referenced. Point 1 from image 1 is referenced to point 1 on image 2 to and point 1 on image 3. The common points in the overlapping images are identified and the bundle adjustment process is performed where the xyz coordinates of each spot are calculated. The coordinates of these points are sent to an algorithm implemented in MATLAB™. The algorithm, described later under *Results and Discussion*, then calculates the slope profile at each point to estimate the overall surface profile.

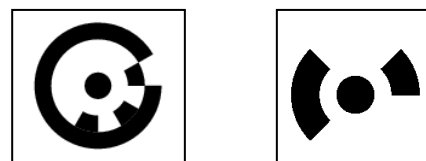


FIGURE 4. Two examples of Coded Targets

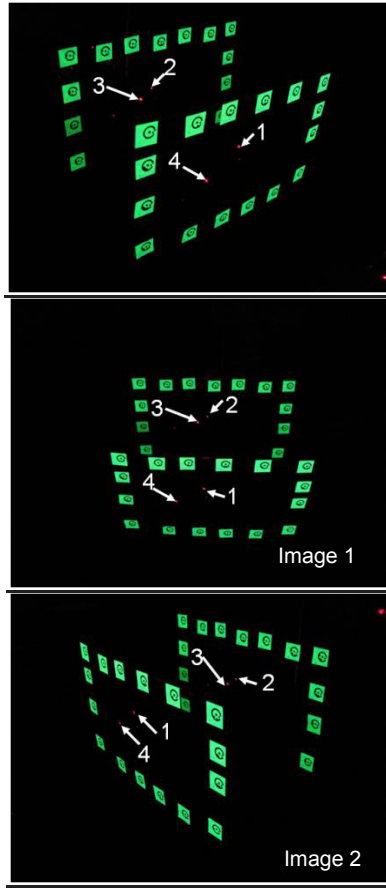


FIGURE 5. Illustration of point referencing.

### Slope Profile Algorithm

The xyz coordinates of the spots on the windows are obtained from the photogrammetry process. Two vectors,  $v_i$  and  $v_r$ , are obtained from the coordinates of the spots where  $v_i$  represents the incident beam and  $v_r$  represents the reflected beam. The angle between the two vectors is calculated from the dot product:

$$\theta = \cos^{-1} \left( \frac{v_i \cdot v_r}{|v_i||v_r|} \right).$$

Also the coordinates of a vector,  $\hat{z}'$ , orthogonal to these two vectors, is calculated from the cross product:

$$\hat{z}' = (v_i \times v_r).$$

From the law of reflection we know that the angle of incidence, with respect to the vector normal to the surface, is equal to the angle of reflection. Therefore the angle of incidence,  $\theta_i$ , is half of the angle between the two vectors,  $\theta$ . The vector for the reflected beam is then rotated

about the orthogonal vector,  $\hat{z}'$ , to give the vector normal to the surface,  $\hat{N}$ . Projecting the normal vector onto a 2-dimensional plane (X-Z), the angle the reflected beam makes with the Z-axis,  $\alpha$ , can be calculated (Figure 6). This gives the incremental surface slopes along the X-axis. Noting the incremental distance ( $\Delta x$ ) traveled in the X-direction (as determined by the encoder on the precision rail), the sag ( $\Delta z$ ) for the particular point on a surface measured can be estimated as:

$$\Delta z = \Delta x \tan \alpha$$

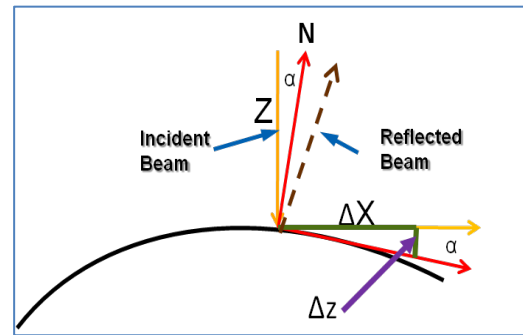


FIGURE 6. Slope profile calculation.

Subsequently, the sag at each point can be summed to obtain an estimate of the total sag, or profile, of the part being measured. This obviously improves with reduced step size.

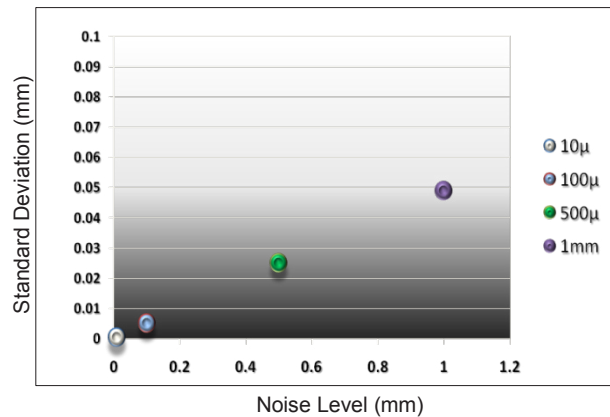


FIGURE 7. Noise simulation for 10  $\mu\text{m}$ , 100  $\mu\text{m}$ , 500  $\mu\text{m}$ , and 1 mm.

The sensitivity of the algorithm to measurement noise was evaluated through simulation. A MATLAB™ program allows the user to visualize beam reflection from simple spherical forms and refraction as it passes through the semi-transparent windows. This program returns the



xyz coordinates of the points where a beam passes through the windows and the angle of incidence with respect to the surface normal. Gaussian noise was added to the xyz values to test sensitivity. This provides an indication of how much noise can be present before the profile measurements are significantly compromised.

Using the reflection simulation program to assess sensitivity, noise levels on the order of 10  $\mu\text{m}$ , 100  $\mu\text{m}$ , 500  $\mu\text{m}$ , and 1 mm were applied to the xyz coordinates generated by the simulation. We simulated the measurement of a 50mm aperture spherical mirror with a nominal sag of 1.21 mm over this aperture, with a measurement step of 2 mm (to match current parameters). For 1000 samples, the peak-to-valley differences, or sag, in the slope profile were calculated. Figure 7 shows the results of standard deviation in the sag values. From this it can be concluded that noise on the level of 10  $\mu\text{m}$  is required to obtain profile results where the standard deviation is around 0.5  $\mu\text{m}$ , or 0.0005 mm out of 1.21 mm (4 parts in  $10^4$ ). This level of noise on the spot coordinates is not unreasonable for photogrammetry.

### Test Details

Three different mirrors were investigated to obtain a figure profile (see Table 1). The profile obtained is the result of rastering the laser across the center of the mirror once. The basic measurement steps involved were 1) align the laser with the mirror center, 2) start the measurement with the laser beam positioned at the edge of the mirror, 3) an image from three camera vantage points are taken of the four spots visible on the windows, 4) translate the laser along the X-axis in increments of 2 mm and capture another set of three images, 5) repeat until the laser has covered the full diameter of the mirror, 6) process the images in MATLAB™ and PhotoModeler™ to extract the xyz coordinates of each of the four laser induced spots, 7) process coordinates in an algorithm to determine the mirror sag or profile along the desired path.

### Results and Discussion

Measurements of three separate spherical mirrors distributed by Edmund Optics Inc. were taken using the system described. Table 1 shows the aperture size of the mirror, the radius of curvature and sag as indicated by the manufacturer, and the preliminary measurement

results. Each measurement was taken at increments  $\Delta x = 2$  mm. Figure 8 shows the results of the profiles. The preliminary test results correlate well to the manufacturer's specifications. It should be noted that profiles with a small radius of curvature, such as the 32 mm concave mirror, would significantly benefit from measurements with smaller step increments.

Noise in the measurement can arise from several factors. First, noise can arise from the optical targets or spots generated by the laser and multimode fibers. As mentioned before, targets must be high contrast for best results. Laser speckle and scatter non-uniformity at the window degrade the uniformity of the photographed spots, and this changes as the beam is rastered over the part. This leads to perceived coordinate shifts of the spots. Second, as the beam passes through the semi-transparent windows, it will refract causing a shift in the beam location. This can be estimated and corrected for and currently is not a limiting factor for the measurement. Finally, noise can be induced by thermal gradients. Vibrations or window displacement are not a great concern because each set of three images is taken nearly simultaneously, with less than 50 ms delay. Our current limitation is the coarse step increment and speckle noise in the laser, and improvements for both are underway.

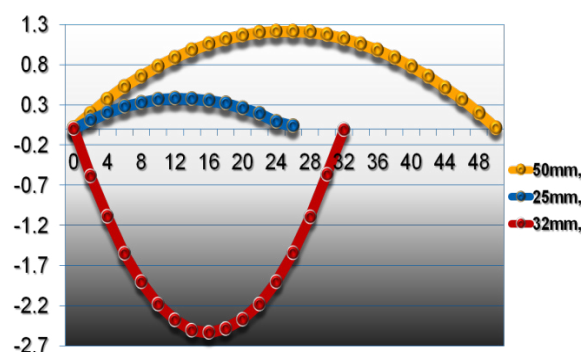


FIGURE 8. Preliminary measurement results for a 50 mm convex, 25 mm convex, and 32 mm concave mirror.

It is noteworthy that the surface finish on the windows created by the sanding caused unwanted flare around the laser beam spot, increasing the noise in the image. Using highly specular tinted windows resolved this problem; however, the specular windows resulted in

unwanted secondary reflections between the surfaces of the windows.

*TABLE 1. Preliminary measurement results for a 50 mm convex, 25 mm convex, and 32 mm concave mirror.*

| Aperture<br>(mm) | Manufacturer<br>Specification |             | Preliminary<br>Results |             |
|------------------|-------------------------------|-------------|------------------------|-------------|
|                  | R<br>(mm)                     | Sag<br>(mm) | R (mm)                 | Sag<br>(mm) |
| 25               | 209                           | 0.37        | 204.173                | 0.383       |
| 32               | 50                            | 2.63        | 51.819                 | 2.532       |
| 50               | 258                           | 1.21        | 258.232                | 1.213       |

An additional experiment was conducted to assess the repeatability in the marking capabilities of Photomodeler™. A set of point coordinate data was taken for a 50 mm diameter, 1.21 mm sag mirror. Again, the incremental distance was 2 mm. A set of photos from three camera viewpoints were taken. The same photos were processed 10 times where the points of interest were marked each time using Photomodeler™. The peak-to-valley sag values were calculated for each of the 10 profiles obtained from the measurement. The standard deviation in these values was calculated to be approximately 7  $\mu$ m.

### **Automation**

Automation is accomplished in MATLAB™ using dynamic data exchange (DDE). With DDE, MATLAB™ can be used as a client application to initiate and maintain conversations with server applications, such as Photomodeler™ and PSRemote. During the initial testing each point had to be manually marked. Though Photomodeler™ has the capabilities to automatically mark targets, it will often mark false, or unwanted, targets created by hot spots or secondary reflections. MATLAB™ is now used to perform some initial image processing to filter out false targets.

The MATLAB™ image processing program is first used to control PSRemote. This gathers the photographs needed from the measurement system. The images are then sent to Photomodeler™ where the photogrammetry process takes place. Here Photomodeler™ is directed to import the desired images, automatically mark the coded targets and orient the cameras. The 7 dot targets, four from the windows and three from the reference length,

are identified (marked) using filtering techniques in MATLAB™. This helps alleviate the automatic marking of false targets in Photomodeler™. The pixel coordinates for the dot targets, as obtained by MATLAB™, are used to mark the images in Photomodeler™. Once all images have been marked, Photomodeler™ is directed to automatically reference each correlating point in the images (Figure 5) to calculate the xyz of the generated spots. These xyz coordinates are then sent to the profile generation algorithm in MATLAB™ to calculate the sag or form of the object being measured.

### **CONCLUDING REMARKS**

We have demonstrated a measurement system capable of indirectly obtaining the profile of specular surfaces. The system was used to measure three spherical mirrors, where the differences in the preliminary results and manufacturer specification were less than 4%. Work to fully automate the measurement process and reduce noise sources is underway. Once completed, the automation process will allow for the full aperture measurements of complex profiles on a machine tool.

### **ACKNOWLEDGEMENTS**

This project is funded by the National Science Foundation under grant #0928364. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

### **REFERENCES**

- [1] Geodetic Services, Inc., "The Basics of Photogrammetry.," <http://www.geodetic.com>, (2010)
- [2] <http://www.Photomodeler.com>
- [3] Gooch R, Optical Metrology in Manufacturing Automation. Sensor Review. 1998;18(2): 81-87
- [4] Luhmann T, Close Range Photogrammetry for Industrial Applications, ISPRS Journal of Photogrammetry and Remote Sensing, 2010; 65: 558-569
- [5] [http://breezesys.com/MultiCamera/psr\\_in-dex.htm](http://breezesys.com/MultiCamera/psr_in-dex.htm)

# NOVEL USE OF A TRADITIONAL MACHINING METHOD FOR GENERATION OF LARGE SCALE MICRO-STRUCTURED SURFACES

Dan E. Luttrell  
Moore Tool Company  
Bridgeport, CT USA

## ABSTRACT

A new method for generating a micro-structured surface on a large drum with a single point diamond tool has been characterized and tested. The fundamental idea is based upon a traditional manufacturing process from the gear making industry. This method enables grooves to be machined on large drums at any angle and within a reasonable amount of time. Of particular interest is the machining of grooves along the longitudinal axis of the drum.

## BACKGROUND AND MOTIVATION

Manufacturing of Brightness Enhancement Film (BEF) for flat panel displays has undergone dramatic growth over the last decade. Total sales of this film are expected to reach \$3B in 2011. This rapid growth is driven by development of Liquid Crystal Display (LCD) products which have become the predominant display technology.

There is pressure to reduce the manufacturing cost of these displays and the enhancement films they contain. This has created several challenging requirements for the machining of large micro-structured drums that are used as master tooling in manufacturing the enhancement film.

The basic structure of BEF is a series of parallel 'V' grooves each with an included angle of 90°. Pitch of the grooves has typically been 50  $\mu\text{m}$  but structures with pitch down to 20  $\mu\text{m}$  are becoming more common for smaller displays like those in handheld devices. Each display contains two pieces of BEF with the grooves in each piece oriented at 90° to the other. FIGURE 1 shows the structure of BEF and the basic construction of an LCD.

The function of BEF is to concentrate light from the Back Light Unit (BLU) toward the viewer and minimize light that is transmitted at large viewing angles. This allows the light source, either florescent tubes or LEDs, to operate at lower power for the same brightness level as seen by

the operator. This prolongs battery life and reduces heat generated since the light source is a major power drain.

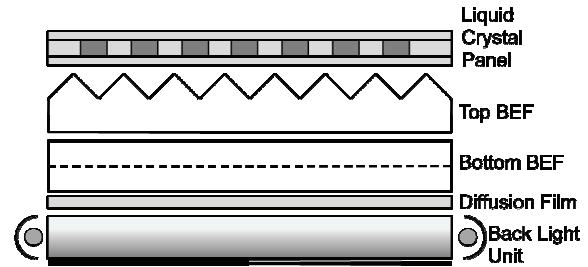


FIGURE 1. Structure of Typical LCD with Backlight and Brightness Enhancement Film.

Manufacturing of the film is a continuous replication process that uses a large cylinder (or drum) with the V groove pattern machined onto the outer surface. A replica of this pattern is formed into soft polymer material on a film as it is wrapped around the drum. As the drum rotates, the soft material hardens and the film is then peeled off the drum.

The V groove pattern is machined on the surface of the drum with a single crystal diamond tool using a large ultra-precision lathe designed for this purpose. The machining process is a continuous thread cut and results in a single groove on the drum. It is done this way because a continuous thread cut requires far less time to complete than a series of plunge cut grooves, and the spiral of the thread, typically 50  $\mu\text{m}$  per revolution, does not affect the film forming process or the final product.

It's also important to note that the machining process requires 2 or 3 passes of the tool in the groove at decreasing depths of cut to achieve the required surface finish. The basic thread cutting process for the V grooves is illustrated in Figure 2 and shown in FIGURE 3.

Film manufactured with this type of drum tooling has the grooves oriented essentially parallel to the edges of the film. When the film is cut (or

converted) into the rectangular pieces for the assembly, these rectangular pieces have to be cut to orient the grooves 90° to each other in the display. During assembly of the display, each piece is handled and assembled separately.

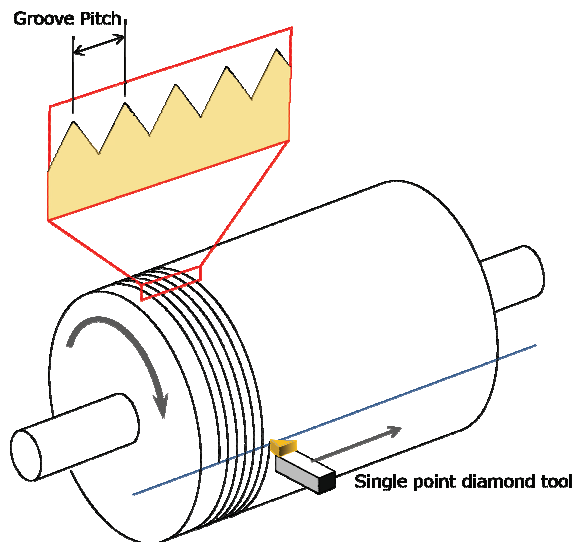


FIGURE 2. Typical thread cutting process.

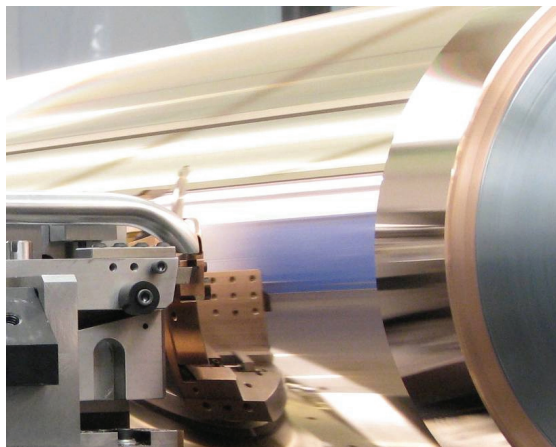


FIGURE 3. Typical thread cutting process on copper drum.

It would be of great advantage to display manufacturers if film could also be made with the grooves oriented perpendicular to the edge of the film. This would enable significant cost reduction in the overall display manufacturing process. To make this particular film requires a large drum with the primary axis of the V grooves oriented along the longitudinal axis of the drum, which is perpendicular to the standard thread cut grooves.

The problem for manufacturers is creating a drum with the V grooves oriented in the longitudinal direction within a reasonable amount of time. Grooves at any orientation can be made on large drums with a straightforward ruling process that coordinates linear motion of the diamond tool with rotation of the drum. The process for ruling longitudinal grooves on a drum is illustrated in FIGURE 4.

The problem is that to machine a large production drum with longitudinal grooves requires more than 8 days of continuous cutting with a standard machine. If a high-speed shuttle axis were available with 3 times the speed of the standard machine axis, it would still require about 6 days to complete a drum. This is about 3 times longer than what manufacturers consider a reasonable time.

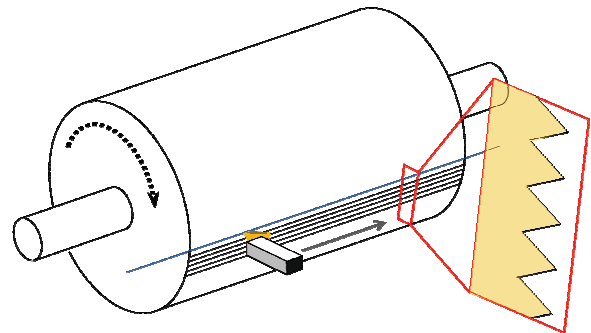


FIGURE 4. Horizontal ruling of V grooves on a drum.

#### DESCRIPTION OF MACHINING PROCESS

To address the problem of excessive machining time, a method was tested which is capable of cutting longitudinal grooves on a complete drum in less than two days [1]. This shorter machining time makes it a feasible process for the manufacturers of enhancement film.

This method is similar to the traditional machining process known as hobbing which is a common process used to make gears and splines. The hobbing process uses a cylindrical cutting tool (known as a hob) with multiple cutting edges around the outer surface which are designed to take progressively deeper cuts to form the gear teeth. The rotational axis of the hob and workpiece are oriented at some angle to each other. This angle depends on the design of the hob and the helix angle of the gear teeth. The hob rotation speed is a multiple of the workpiece rotation speed and this multiple



establishes the number of teeth generated. Together, the orientation and speed difference, along with the hob design, allows the hob to generate gear teeth in a relatively short period of time.

The method developed for diamond machining longitudinal V grooves on a drum uses a rotating cutting tool in an orientation similar to that of the cutting tool in gear hobbing. In its simplest form the cutting tool is a single crystal diamond tool with a 90° V shape and this is mounted on the outer edge of a rotating disk (or flycutter). The diamond is oriented on the flycutter so the V points in the radial direction and a line normal to the rake face points in the direction of rotation. This could be referred to as single point hobbing or “flycutter hobbing” [2].

The rotational axis of the flycutter is approximately 90° to the drum rotation axis as illustrated in FIGURE 5. The flycutter rotation and drum rotation are synchronized so the flycutter speed is some multiple of the drum speed, and this multiple establishes the number of grooves on the circumference of the drum.

The number of grooves is determined by the drum circumference and the desired groove pitch. For example, a drum with a circumference of 1 meter (diameter = 318.31 mm) and 50 μm pitch longitudinal grooves would have a total of 20,000 grooves around the circumference. For this example, the flycutter would rotate 20,000 times for each rotation of the drum.

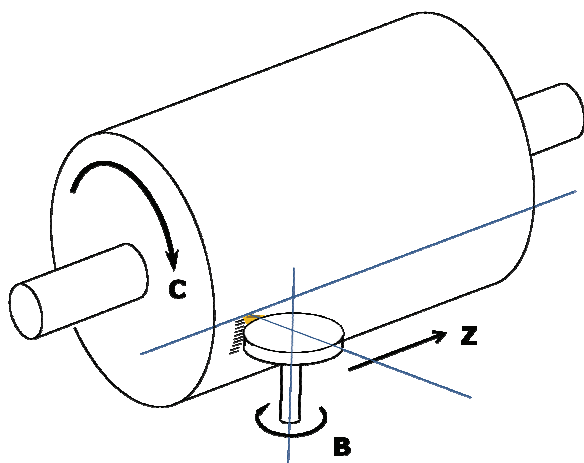


FIGURE 5. Layout of single point diamond flycutting.

For this process, the flycutter is rotating at a fairly high speed and the drum rotated slowly

and continuously. For each rotation of the flycutter, the drum rotates only the small amount needed so that the drum surface has moved a distance equal to the pitch of the grooves. Each time the tool contacts the drum surface and makes a cut, it forms a small portion of each V groove, but it does so at the full depth of the groove.

In a normal groove flycutting process, each groove is machined one at a time with the flycutter tool moving along the major axis of the groove. Each time the cutting tool comes in contact with the workpiece, it cuts a portion of the same groove. At the end of each groove, the flycutter is retracted away from the workpiece and moved back to the beginning of the next groove. This sequence is repeated for each individual groove.

In the drum flycutting process, the workpiece surface is moved perpendicular to the flycutter tool by the rotation of the drum. Each time the cutting tool comes in contact with the drum it cuts a portion of adjacent grooves. This is the key difference between normal groove flycutting and the “flycutter hobbing”.

To form complete grooves, the flycutter is slowly advanced along the longitudinal axis of the drum so that for each revolution of the drum, a small portion of each groove is machined. A single groove is formed by cuts of the tool that occur only once per revolution of the drum. It requires very precise coordination of the drum and flycutter rotation to achieve the synchronization needed to align the cutting tool to each groove.

Distance the flycutter advances for each revolution of the drum determines the tool overlap within each groove. This overlap is an important factor in the process since the tool follows a circular arc. This leads to a depth variation in the grooves generally known as cusping.

Theoretical height of the cusping is determined by the overlap distance and the radius of the path followed by the tip of the cutting tool. This height is given by the following:

$$h = F^2/8r$$

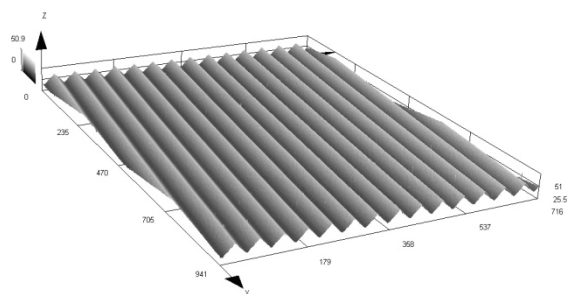
where  $h$  is the height deviation of the bottom of the groove,  $F$  is the flycutter feed per revolution

of the drum, and  $r$  is the radius of the path followed by the tip of the cutting tool. This is similar to calculating the theoretical finish of a surface machined with a round-nose tool.

### INITIAL MACHINING RESULTS

Machining tests were conducted on a small, nickel plated test drum using a single cutting tool on a flycutting spindle. The objective was to machine longitudinal grooves with 50  $\mu\text{m}$  pitch and a 90° included angle (a typical BEF pattern). Various spindle speeds and overlap distances were tested.

After machining, high fidelity replications were made of the surface using the Repliset material from Struers. These were examined with a confocal microscope and measurements made of the groove shape and pitch. FIGURE 6 is an image from one of the measurements. This image shows an area 941 mm x 716 mm which was large enough to encompass a number of overlaps, or cusps, within the grooves.



**FIGURE 6.** *Confocal microscope image of longitudinal V grooves made by flycutter hobbing process.*

Images and measurements made of initial test patterns were better than expected. The confocal microscope was not able to discern any of the cusping over the range of heights that were machined. Pitch of the grooves was measured to be  $50 \pm 0.25 \mu\text{m}$  and well within the required tolerance.

### DISCUSSION

The flycutter hobbing method has other benefits besides reducing overall cycle time. One key benefit is reducing tool wear. This not only improves the overall quality of the entire structured surface but makes it possible to directly machine harder materials such as nickel. This is a benefit of considerable importance to the manufacturers of enhancement film.

The flycutter hobbing method can be set up to machine grooves at almost any helix angle. This would be similar to the gear hobbing process for generation of helical gears. The flycutter would have to be tilted at some angle relative to the longitudinal axis of the drum and the synchronization of the two spindles would have to be modified accordingly.

This method also enables variation in groove depth without the use of a Fast Tool Servo. In addition, it has the possibility to enable the generation of other structures on large drums beyond the standard BEF pattern. One such pattern is a seamless retro-reflective corner cube pattern.

### REFERENCES

- [1] Burke JP, Campbell AB, Ehnes DL, Wertz DS, inventors; 3M Innovative Properties Co., assignee. Fly-cutting system and method, and related tooling and articles. US Patent Application Publication 11/834,371. 2009 Feb 12.
- [2] Klocke F, Winkel O. New potentials in carbide hobbing. *Gear Technology*. 2004 Jan/Feb.

# FREEFORM MICROSTRUCTURED STAINLESS STEEL MOLDS

Andrew H Cannon, March Maguire, and William P King

Hoowaki LLC

Pendleton, SC, USA

Email: [andrew@hoowaki.com](mailto:andrew@hoowaki.com) | Phone: 864.569.8875 | Fax: 864.646.2178

Micro and nanostructured surfaces can affect many surface attributes including tribological characteristics, optics, heat transfer, and water repellency. Molding micro and nanostructures into surfaces is a scalable route to manufacturing microstructured freeform surfaces. This paper describes how microstructured stainless steel molds with freeform surfaces can produce microstructured replicates with an emphasis on superhydrophobicity.

Microstructured stainless steel molds can have microholes or micropillars depending on the specific application. Figure 1 shows a stainless steel mold insert with micropillars on a two dimensional curved surface. The mold is durable because it is 174PH stainless steel, and the microstructures have geometry suitable for superhydrophobicity because of the designed and well controlled microstructure diameter, spacing, and height.

Superhydrophobicity is the extreme water repelling ability of some natural surfaces like the lotus leaf [1, 2] and synthetic surfaces that mimic the surface structure and chemistry of the lotus leaf [3]. Figure 2 illustrates the concept of how surface microstructures affect the water repelling characteristics of a surface. When a surface becomes rough with patterned microstructures, the surface microstructures affect the way that water interacts with that surface. In the presence of microstructures, a surface that repels water ("phobic") becomes more water repelling and a surface that attracts water ("philic") becomes more attractive.

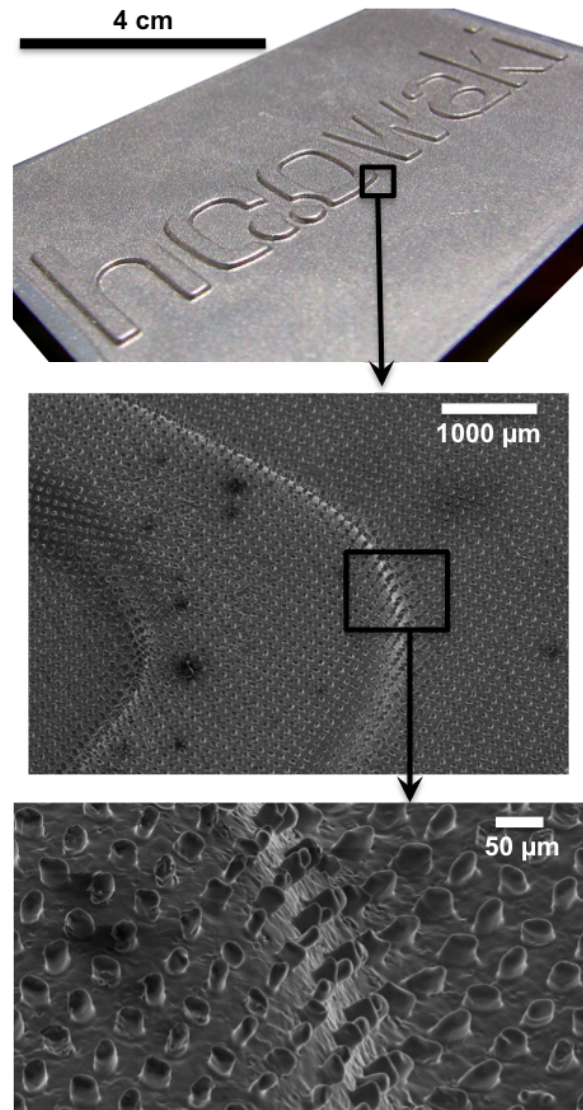
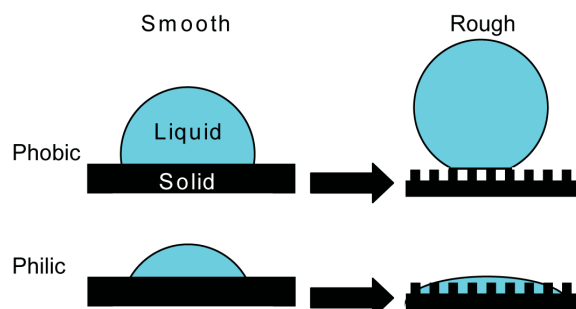
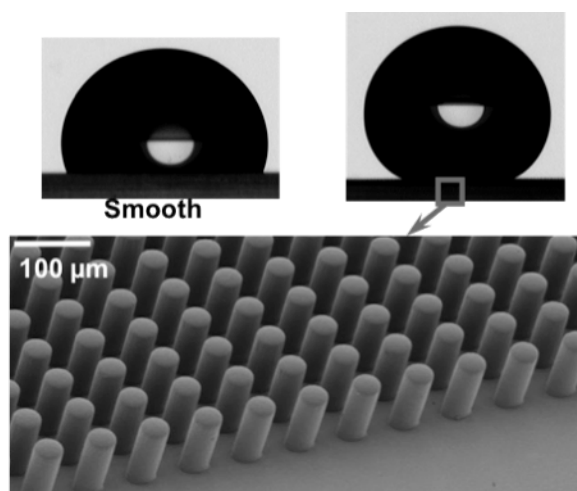


FIGURE 1. Stainless steel micropillars with two dimensional curved surfaces. Hoowaki produces stainless steel tools with flat and curved surfaces with microholes and micropillars.



**FIGURE 2.** Surface roughness amplifies natural surface chemistry.

Figure 3 shows fabricated silicone rubber micropillars that rendered the normally hydrophobic silicone superhydrophobic. While the smooth polymer originally had contact angle  $\theta = 112^\circ$ , the microstructured polymer has  $\theta = 152^\circ$ . Using inexpensively fabricated superhydrophobic products to protect expensive equipment could mitigate the cost of corrosion. The National Association of Corrosion Engineers estimates corrosion consumes 3% of the Gross Domestic Product of the United States annually [4]. Superhydrophobic surfaces can also exhibit “self-cleaning” properties because droplets that roll off of the surface carry away particles that are larger than microstructure spacing [1]. Superhydrophobic microstructures such as those shown in Figure 3 have been used to decrease drag [5, 6] and reduce ice thickness and adherence [7].



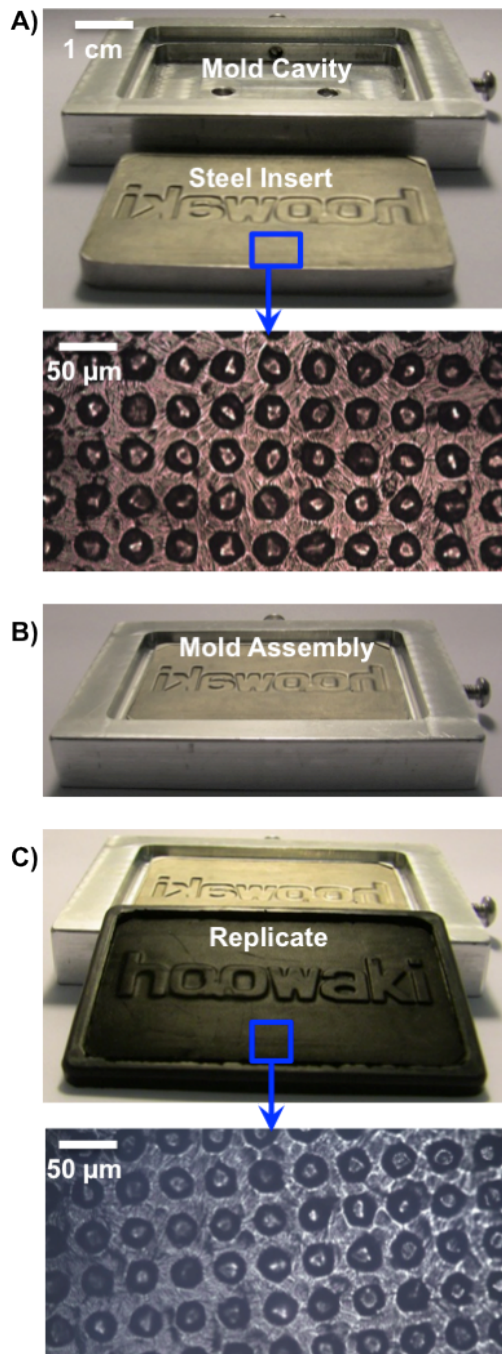
**FIGURE 3.** Micropillars molded into silicone rubber cause an increase in contact angle and render the silicone superhydrophobic

Hoowaki produces flat and curved molding tools for molding superhydrophobic structures into polymers such as santoprene that is used

extensively in automobiles. The tools can be used in a press or as an injection mold insert. As Figure 4 shows, the process of molding a superhydrophobic polymer surface begins with a mold cavity and a microstructured steel insert. The steel insert is assembled with the mold cavity, and polymer is molded in the assembly. A polymer replicate results having microstructures from the steel insert. The microstructures shown in Figure 4 cause superhydrophobicity demonstrated in Figure 3.

The microstructures Hoowaki produces range in size from  $2\text{ }\mu\text{m}$  to  $200\text{ }\mu\text{m}$ , and the molding tools range in macro size from 1” to 6” and can be machined to fit specific applications. The materials Hoowaki can microstructure include stainless steels, tool steel, nickel, titanium, copper, and carbide steels.





**FIGURE 4.** Production of microstructured superhydrophobic molded parts using microstructured steel mold inserts. A) The process begins with a mold cavity and a microstructured steel insert. B) The steel insert is assembled with the mold cavity, and polymer is molded in the assembly. C) A polymer replicate results having microstructures from the steel insert. The microstructures shown here cause superhydrophobicity demonstrated in Figure 2.

## ACKNOWLEDGEMENTS

Hoowaki thanks the National Science Foundation and the South Carolina Research Authority for funding the present work.

## REFERENCES

- [1] Neinhuis, C. and W. Barthlott, *Characterization and Distribution of Water-repellent, Self-cleaning Plant Surfaces*. Ann Bot, 1997. **79**(6): p. 667-677.
- [2] Quere, D., *Non-sticking drops*. Reports on Progress in Physics, 2005. **68**(11): p. 2495-2532.
- [3] Cannon, A.H. and W.P. King, *Hydrophobicity of curved microstructured surfaces* Journal of Micromechanics and Microengineering, 2010. **20**(2): p. 025018.
- [4] Koch, G.H., et al., *Corrosion costs and preventative strategies in the United States*. 2002, National Association of Corrosion Engineers (NACE)
- [5] Watanabe, K., *Fluid frictions of shark skin and lotus leaf - How does the drag reduction occur?* Journal of Japanese Society of Tribologists, 2000. **45**(5): p. 354-359.
- [6] Wilson, M., *Superhydrophobic Surfaces Reduce Drag*. Physics Today, 2009. **62**(10): p. 16-19.
- [7] Cao, L., et al., *Anti-icing superhydrophobic coatings*. Langmuir, 2009. **25**(21): p. 12444-12448.

# INJECTION MOLD PROCESS OPTIMIZATION FOR SURFACE MICROFEATURE CONTROL

Manjesh Dubey<sup>1</sup>, Laine Mears<sup>1</sup>, Andrew Cannon<sup>2</sup>, and Ralph Hulseman<sup>2</sup>

<sup>1</sup>Department of Automotive Engineering

Clemson University

Greenville, SC, USA

<sup>2</sup>Hoowaki, LLC

Greenville, SC, USA

## INTRODUCTION

A method for creating regular arrays of surface features in the 10 $\mu$ m to 200 $\mu$ m range over large areas in metallic materials enables the use of treated surfaces on injection molds. This surface control is used for manufacturing products with controllable optical, tribological, heat transfer, and surface tension properties. However, the flow, filling, and solidification behavior of molten polymer at the micro scale is not well understood.

Therefore, the purpose of this study is to derive a range of robust solutions for injection molding of these micro-featured surfaces. The approach includes numerical simulation of flow under different molding conditions, which drives input variable and range selection of a large design of experiments study. This study uses critical inputs of the molding process, mold geometry, and working materials, and determines a range of feasible solutions to recreate these micro structures without filling or demolding defects. Five different molding parameters hypothesized as most influential in molding microstructures were varied and the resultant micro-features characterized using 3D surface profiling white light interferometry and scanning electron microscopy. Regression responses were determined and optimal value ranges for the key input parameters were identified and independent tests run to verify the results. The five parameters tested are: injection pressure, injection velocity, mold temperature, melt temperature and shape of micro structures. These tests were carried out in both HDPE and EPDM/PP alloy [1] materials using different mold insert materials and coatings.

The results obtained from these tests gave us a clear indication of how each of the above parameters controls the formation of molded microfeatures, and how parameters interact. In this case mold temperature was found to be the most critical factor, with a sensitivity of only a

few degrees greatly improving the micro feature formation. The biggest concern was uniformity of micro features across the molded surface. Based on this understanding we were also able to simulate macroscopic mold filling conditions and verify homogeneous filling across the molded surface. These experimental results are used to drive a predictive tool for process planning of complete undamaged feature formation at the micro scale and uniformity at the macro scale.

## MICROFEATURE MOLD DEVELOPMENT

The injection mold inserts were fabricated by Hoowaki LLC using a process with certain proprietary segments. The process begins with silicon micro-fabrication to create an original silicon mold. Because the silicon is brittle, a series of intermediate materials are cast, molded, and formed to create the durable nickel and steel molds used in the present study [2]-[4].

## REVIEW OF MICROFEATURE MOLDING

### Embossing Pillars

In the past the impact of polymer film thickness and cavity size on polymer flow during embossing of similar micro features has been studied for the nanoimprint lithography process [5]. It was found that polymer deformation and fill time is governed by location and rate of polymer shear during imprinting, exhibiting deformation predominantly close to the vertical side wall that can result in either single peak or dual peak deformation modes. There is no reference to observation of such modes in micro-injection molding.

### Microinjection Molding

Chu et al. [6] investigated the effects of various injection molding process parameters on the micromolding process and part quality. They

estimated the processing conditions during the cavity filling stage in a plunger micro injection molding system by using short-shot trials and by analyzing the data obtained from tracing the evolution of injection pressure, runner pressure, and plunger position, at the millisecond time scale. They did this study for three different polymers: POM, HDPE, and PC and through statistical analysis found injection speed to be most significant factor while the effects of mold and melt temperature varied from material to material.

In our study although Injection velocity appeared to be a significant factor, mold temperature was found to be most significant factor for injection molding micro-features.

## DESIGN OF EXPERIMENTS APPROACH

**Step 1:** A two cavity injection mold was designed to produce flat rectangular test pieces (44mm x 24mm). Micro features were produced by placing patterns with 20 to 100 micron holes inside the cavities.

**Step 2:** Mold material and coating were screened for measures of goodness related to uniformity of micro features on the pattern, transferability and demolding. Several different materials were tested and summary results shown in Table 1.

Table 1. Pattern material characteristics

| Material                      | Uniformity of micro-features on patterns | Transferability of micro-features to injection molded surface | Remarks                |
|-------------------------------|------------------------------------------|---------------------------------------------------------------|------------------------|
| Silicon rubber                | Good                                     | Average                                                       | De-molding issues      |
| Epoxy                         | Average                                  | Bad                                                           | High de-molding issues |
| Stainless steel               | Good                                     | Good                                                          | No de-molding issues   |
| Teflon coated stainless steel | Good                                     | Very good                                                     | No de-molding issues   |
| Ni coated copper              | Very good                                | Very good                                                     | Excellent de- molding  |

Based on these results, stainless steel and Ni coated copper were selected as pattern material for the extended study.

**Step 3:** A fractional design of experiments (DOE) study was carried out to quantify the effect of the following injection molding parameters on microfeature formation: injection pressure, melt temperature, mold temperature, injection velocity, and cavity thickness. In addition to these, the effect of shape and size of micro-features was also tested.

The quality of micro-feature formation / transferability was determined by analyzing the injection molded surface under Zygo White-Light 3D Surface Profiler. This was done by measuring the height of micro-features at 3 different locations over the molded surface to test uniformity and to see whether or not the target height has been achieved.

In order to understand the effect of macro flow characteristics on the formation of microfeatures, the same test was carried out with component thickness of both 1.5mm and 3.5mm.

Two different polymers, HDPE and EPDM/PP alloy were used for the tests. The feature height  $H$  was recorded in area 1, 2, and 3 and denoted in Figure 1.

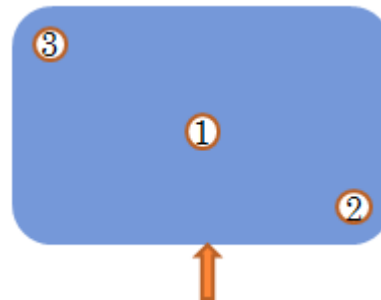


Figure 1.  $H_1$ ,  $H_2$ , and  $H_3$  represent the sample feature height in area 1, 2 and 3 respectively; the arrow denotes the gate position.

The sensitivity plot shown in Figure 2 represents the response height variation with injection pressure for HDPE material. In this plot, the dashed line represents the mold depth compensated for expected material shrinkage. The effects of the other molding parameters on micro-feature formation have been represented similarly.

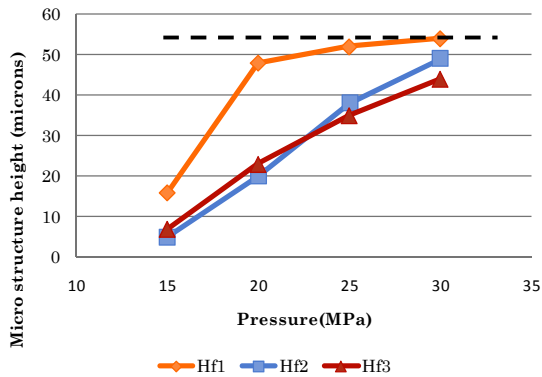


Figure 2. Effect of injection pressure variation on micro-feature height formed with HDPE

The same single-variable response in EPDM/PP alloy material is shown in Figure 3.

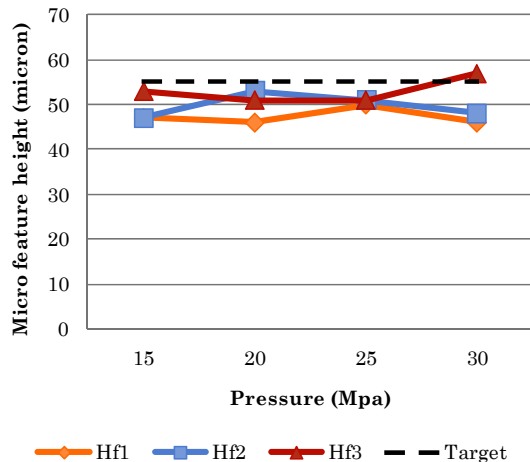


Figure 3. Effect of injection pressure variation on micro-feature height formed with EPDM/PP alloy.

It is apparent that material properties will have a significant interaction effect. Therefore, material-specific regression models are created for the materials tested.

## Results

Multi-variable regression is performed for both HDPE and EPDM/PP alloy materials by ANOVA identification of significant factors and model reduction to include only significant variables and interactions. The resultant model for prediction of feature height in the center of a test sample in HDPE with circular micro features is

$$H_1 = -1031.7 + 18.7P + 2.49T_0 + 2.24V - 0.37P^2 \quad (1)$$

In this model, injection pressure ( $P$ , MPa), injection velocity ( $V$ , mm/s), and mold temperature ( $T_0$ , K) are significant. The model accounts for 83% of the variation observed in microfeature height. The most significant parameters are injection pressure and mold temperature. The model predictions vs. experimental runs are shown in Figure 4.

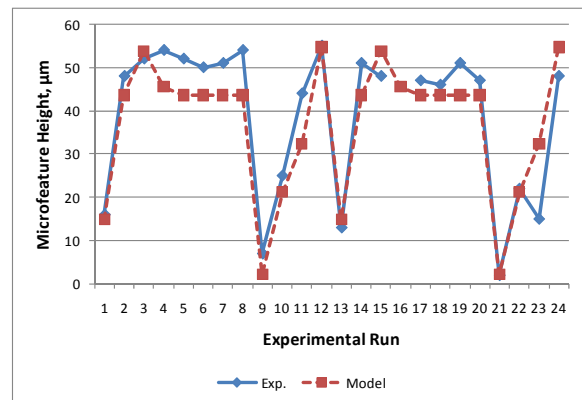


Figure 4. Regression model prediction of microfeature height in plate center (Mold 002A, circular features, HDPE material).

## Optimization

For macro molding the range for the tested parameters seems high when compared with traditional injection molding practice. For example the component looks same at both 15 MPa injection pressure and 30 MPa injection pressure without micro-features; however in the case of micro molding we screened experiments for a wider range of values than traditionally used. The developed regression model was used to plan a feasible process setting for maximum feature height. As discussed in the measurement section, we also observed anomalous “spike” features at the microfeature edges; the optimal process was also designed to minimize this spike height. The resultant optimized value for micro-feature formation with HDPE was: Injection pressure 25 MPa, Injection velocity 20 mm/sec, Melt temperature 280°C and Mold temperature 140°C.

This parameter setting was tested across a range of mold materials and coatings. Component thickness, shape and size of micro-features did not affect the process much at the optimized value; well-formed micro-features



were obtained irrespective of changes in component thickness, shape and size of pores in patterns.

## MEASUREMENT VALIDATION

### Surface Height Geometry

When the micro-features formed by injection molding were analyzed under Zygo White-Light 3D Surface Profiler some spike like features were observed, mostly at the edges. The amount of these spike like features decreased when Ni-Cu patterns were used for molding. However when the same samples were observed under SEM no evidence of spikes was found. A SWLI image of a part with numerous spike anomalies is shown in Figure 5, and a part with few spikes is given in Figure 6.

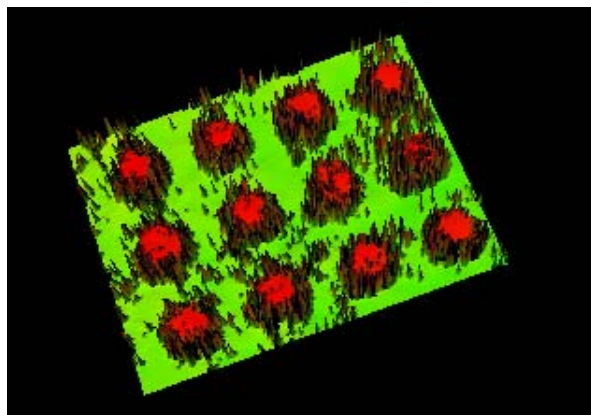


Figure 5. 3D surface profile of micro-features formed with stainless steel template showing spike like structure at the edges.

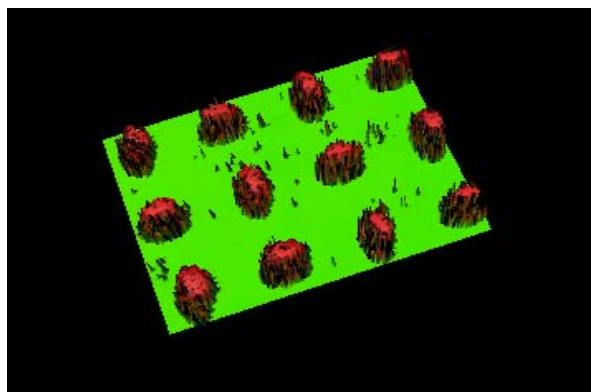


Figure 6. 3D surface profile of micro-features formed with Nickel coated Copper template showing reduced spike like structure at the edges.

Initially it was hypothesized that the spike features were demolding defects due to adhesion at the feature wall, as some observation of tearaway microfeatures that remained in the mold had been observed in extreme cases. Investigation of these anomalies was carried out using scanning electron microscopy but no evidence of such spike like structures was found under SEM giving rise to a possibility that these structures might just be measurement artifact resulting from software issue where the sharp high aspect features were out of bounds for some light reflection data smoothing algorithm used by the SWLI. An SEM image of a “spiky” part is given in Figure 7.

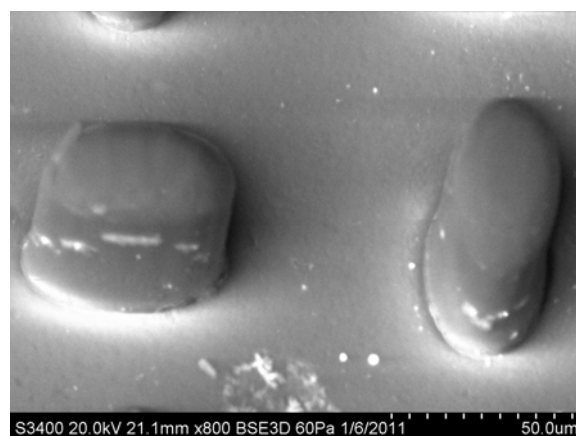


Figure 7. SEM Image of Formed Structures. The structures filled completely, some geometric inconsistencies were noted at the outer edges but there was no evidence of spike-like structures.

### Microscopic Observations

SEM images validated our findings about the effect of various injection molding parameters such as injection pressure, melt temperature, mold temperature, and injection velocity on formation/transferability of micro-features. Figure 8 shows a representative comparison of HDPE samples for high and low values of the levels tested.

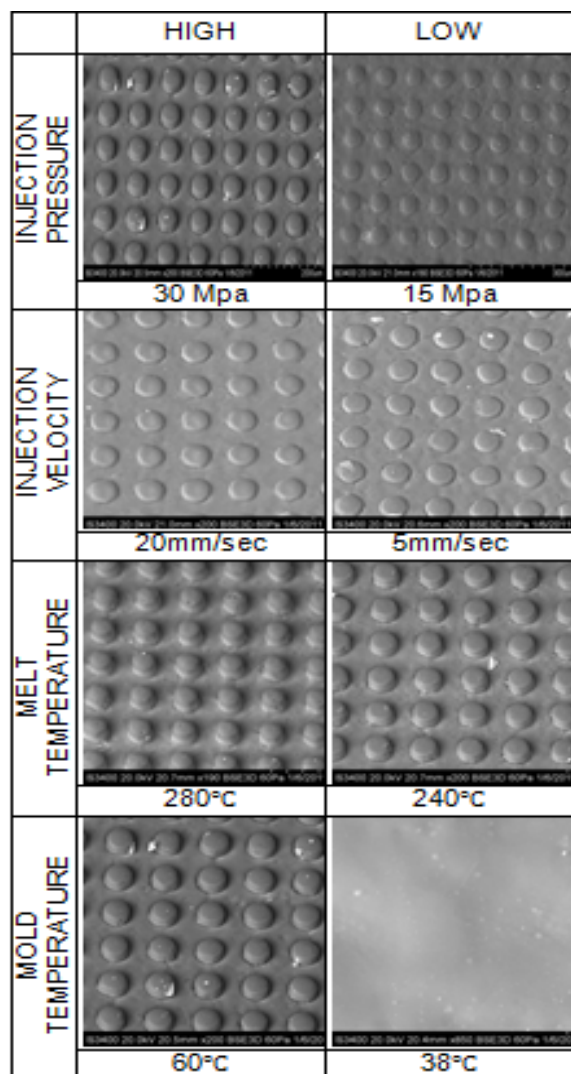


Figure 8. SEM Images of injection molded micro-features at various test conditions.

Injection pressure shows fully-formed structures at the higher level; melt temperature variation had little effect, and mold temperature variation was significant. This is consistent with the regression model results.

The feasible process input values determined from the regression model were run, with geometric results shown in Figure 9. Structures are fully formed and geometrically consistent. Some surface inconsistencies in the formed micro-features can be attributed to the features present in the molding template itself as shown in Figure 10.

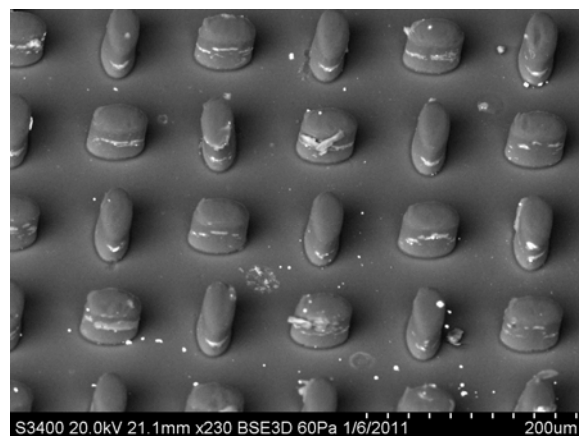


Figure 9. Microscopic Image of Formed Structures at optimal condition. The structures filled completely, but some geometric inconsistencies were noted at the outer edges.

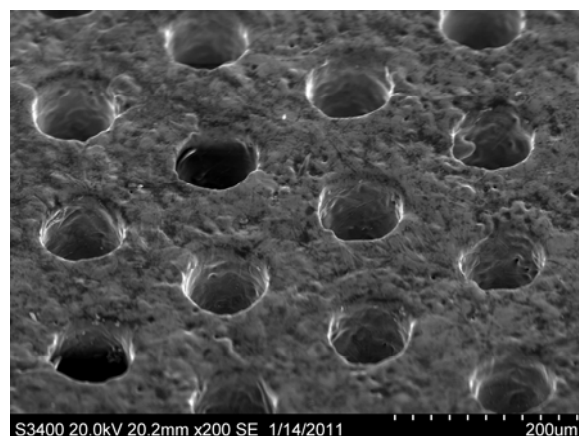


Figure 10. Microscopic Image of holes in molding templates showing inconsistencies in formed micro-features. Similar templates were used for experiments.

## MACROSCOPIC FLOW SIMULATION

We tried to simulate the filling process for micro-features using Autodesk Moldflow and compare results with experimental data obtained, but were unable to simulate the process at such micro level mainly due to meshing limitations. However, we were able to simulate macroscopic filling of the mold cavity and predict packing pressures, temperature and viscosity at filling for different mold conditions. An example macroscopic simulation is shown in Figure 11.

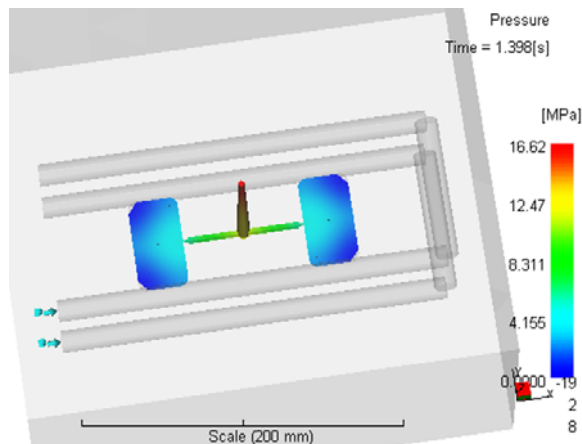


Figure 11. Simulation of pressure distribution at filling, HPDE material.

The predicted pressure profile variation used in the regression predictive model corresponds with variation in height observed at different points across the specimen (see Figure 1).

## CONCLUSIONS

This study was used to derive a range of robust solutions for injection molding of micro-featured surfaces with different polymers. Feasible conditions to form these micro-features were obtained for two different polymers, HDPE and EPDM/PP alloy.

Using Design of Experiments technique, a regression model was derived for predicting the height of surface microfeatures in an HDPE injection molding operation. Similar models are also derived for height prediction in different areas of the mold and in a second material. Future work will continue this effort in a wider range of polymer and mold materials.

Future work in flow simulation for microfeatures will be to isolate and scale the microfeatures for accurate meshing, while maintaining constant nondimensional flow properties (e.g., Reynolds number) for accuracy. Also, the numerical simulation results will be combined with the different regression analyses to improve the distribution of height predictions and make a better feasible process plan.

Reasons for the surface residue or delamination appearance are being investigated.

## ACKNOWLEDGEMENT

The authors would like to thank Kim Campbell-Djuric and Ed Martin of Autodesk for providing training and the use of Moldflow software for this work.

## REFERENCES

- [1] Santoprene 121-M 50, Exxon-Mobil Corp.
- [2] Cannon, A.H., et al., "Molding ceramic microstructures on flat and curved surfaces with and without embedded carbon nanotubes." *Journal of Micromechanics and Microengineering*, 2006. 16(12): p. 2554-2563.
- [3] Cannon, A.H. and W.P. King, "Casting metal microstructures from a flexible and reusable mold." *Journal of Micromechanics and Microengineering*, 2009. 19(9): p. 095016.
- [4] Cannon, A.H. and W.P. King, "Microstructured Metal Molds Fabricated via Investment Casting." *Journal of Micromechanics and Microengineering*, 2010. 20(2): p. 025025.
- [5] Rowland, H.D., et al., "Impact of polymer film thickness and cavity size on polymer flow during embossing: toward process design rules for nanoimprint lithography." *Journal of Micromechanics and Microengineering*, 2005. 15(12): p. 2414-2425.
- [6] Jingsong Chu, Musa R. Kamal, Salim Derdouri, Andy Hrymak, "Characterization of the Microinjection Molding Process." *Polymer Engineering and Science*, 2010 p.1214-1225.

# PRODUCTION AND MEASUREMENT OF ENGINEERED SURFACES FOR USE IN INERTIAL CONFINEMENT FUSION RESEARCH

Robert D. Day, Douglass J. Hatch, and Gerald Rivera  
Materials Science and Technology Division  
Los Alamos National Laboratory  
Los Alamos, New Mexico, USA

## INTRODUCTION

Inertial Confinement Fusion uses the optical energy from a very high power laser to implode spherical capsules that contain a fuel mixture of deuterium and tritium. The capsules are made of either Beryllium, plastic, or glass and range from 0.1 mm to 2 mm in diameter. As a capsule implodes, thereby compressing the fuel to reach nuclear fusion conditions, it achieves temperatures of millions of degrees Centigrade and very high pressures. In this state, the capsule materials act like fluids and often a low density fluidic material will push on a higher density material which can be a very unstable condition depending upon the smoothness of the interface between the two materials. This unstable condition is called a hydrodynamic instability which results in the mixing of the two materials [1], [2]. If the mixing occurs between the fuel and a non-fuel material, it can stop the fusion reaction just like adding significant amounts of water to gasoline can stop the operation of an automobile.

Another region in the capsule where surface roughness can cause capsule performance degradation is at a joint. For instance, many capsules are made of hemispheres that are joined together. If the joint surfaces are too rough, then there will be an effective reduction in density at the joint. This density reduction can cause a non-uniform implosion which will reduce the fusion energy coming out of the capsule.

## HYDRODYNAMIC INSTABILITY SURFACES

Hydrodynamic instabilities are not well understood; therefore, Los Alamos National Laboratory has conducted numerous experiments to gain a better understanding of how these instabilities are initiated and grow at typical fusion conditions. The experimental packages for one set of these experiments required surfaces to be generated with specific power spectra and average roughness values [3], [4]. These specific surfaces were produced on the outside of aluminum marker

layers that had inner diameters of 0.5 mm and were 12  $\mu\text{m}$  thick. The shapes of the specific power spectra required ranged from: 1) flat over a specific spatial wavelength band to 2) flat over specific wavelengths with a peak at a specific wavelength, to 3) a peak at a specific frequency. A variety of amplitudes, frequencies, and roughness values were required for these experiments. A fast-tool-servo (FTS) [5], mounted to an ultra-precision lathe, was used to generate these surfaces. A photograph of one of these packages is shown in Figure 1.

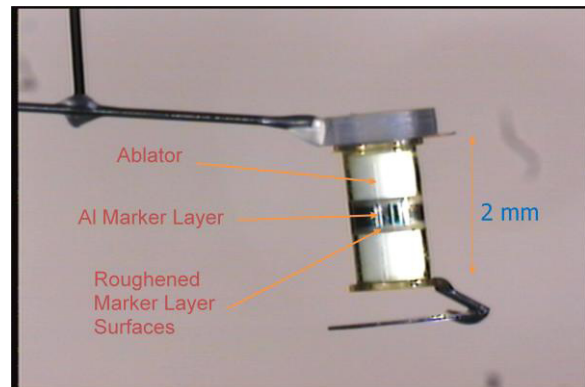


FIGURE 1. Photograph of experimental package used for developing understanding of hydrodynamic instabilities.

## Surfaces with a Flat Power Spectrum

Some surfaces required a flat power spectrum in the wavelength range from 10  $\mu\text{m}$  to 100  $\mu\text{m}$ . The average roughness values for these surfaces ranged from 0.5  $\mu\text{m}$  to 1.0  $\mu\text{m}$ . The cutting tool required to accomplish this should have a maximum width of 5  $\mu\text{m}$  at a distance of 4  $\mu\text{m}$  away for the tip. A three-sided pyramidal shaped single crystal diamond Scanning Tunneling Microscope (STM) tip with face elevation angles of 70° and a flat area at the tip of 75 nm meet this criterion, so it was used as the cutting tool for these surfaces. A mathematical simulation of a surface generated by this tool, with its corresponding power



spectrum, was produced. This power spectrum was shown to the experimenters and determined be good enough to proceed with the production of the surfaces. A random number generator, coupled with the appropriate limit values to give the average roughness value desired, was used to provide voltages to the FTS controller. This moved the tool randomly at a rate of 100 points per second. The spindle rotation speed and the tool federate were adjusted to give a point spacing of 5  $\mu\text{m}$  on the part. The resulting surface and its corresponding power spectrum are shown in Figures 2 and 3, respectively.

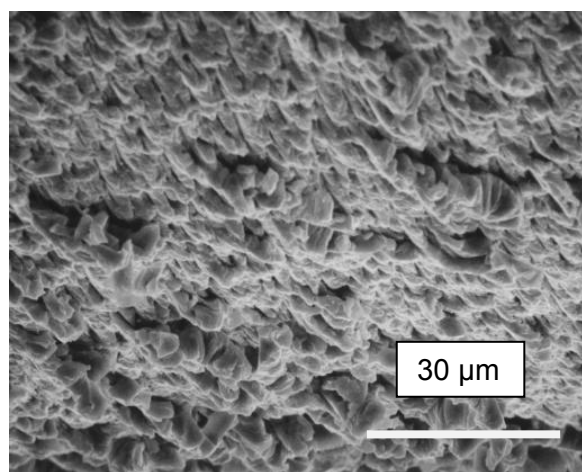


FIGURE 2. Scanning Electron Micrograph of generated random surface.

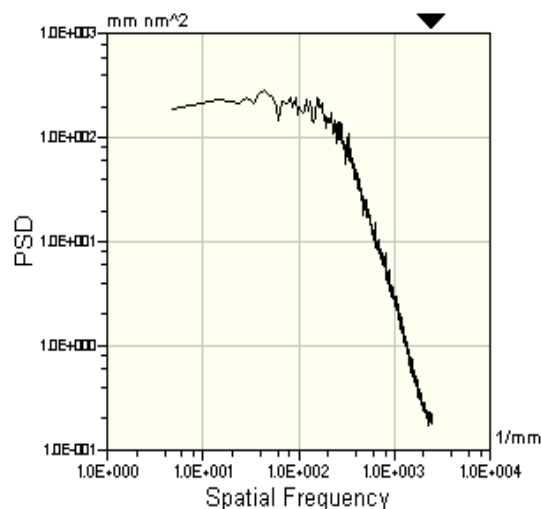


FIGURE 3. Power spectrum of surface shown in Figure 2.

Figure 3 shows that the power spectrum was flat over the wavelength range of 5  $\mu\text{m}$  to 250  $\mu\text{m}$ . The experimenters were very happy with this result.

One set of surfaces needed a peak at a wavelength of 10  $\mu\text{m}$ . This was accomplished by having the FTS operate in the same fashion as described for the flat power spectrum and programming a tool path that consisted of a sine wave with a 10  $\mu\text{m}$  wavelength parallel to the longitudinal axis of the cylinder.

#### Measuring the Thickness of the Marker Layer

After the surfaces had been produced, the thickness of the aluminum marker layer had to be measured. The surface roughness was a significant percentage of the layer thickness, so providing a single number for the thickness was difficult. In the surface roughness region, the density transitions from full density in the bulk material to zero density. This is illustrated in Figure 4 where the surface roughness region is represented by a set of conical-shaped objects. Region A is the full density bulk material. In region B the effective density of the material goes from full density, near A, to zero density at the peaks of the cones.



FIGURE 4. Illustration of transition from full density material in region A to zero density material at the peaks of the cones in region B.

The Bearing Area Ratio measures the effective density of the material as a function of height through the surface roughness region (region B). This is done by measuring the area of material at a specific height and dividing that area by the total area. This is illustrated in Figure 5 where the conical features of Figure 4 are sliced at a certain height to reveal the area of full density material at that height. An example of a measured Bearing Area Ratio plot is shown in Figure 6.

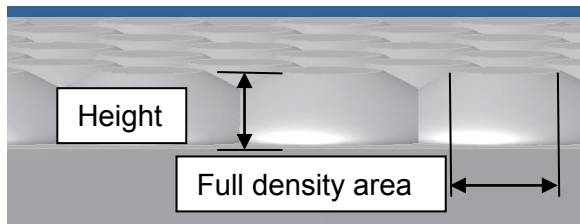


FIGURE 5. Illustration of bearing area.

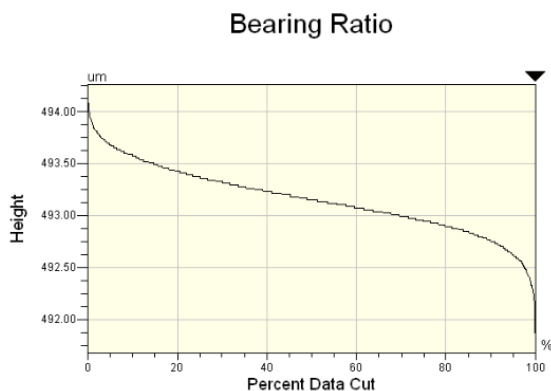


FIGURE 6. Typical Bearing Area Ratio plot.

Since, density is an important parameter for this set of experiments it was decided to measure the effective density profile and use the value where the effective density is 50% of full density as the layer thickness. A plot of the normalized effective density of a marker layer is shown in Figure 7. So, the marker layer thickness would be where the normalized effective density is 0.5. This occurs at a thickness of 14  $\mu\text{m}$ .

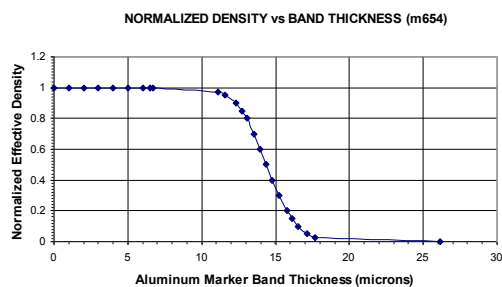


FIGURE 7. Normalized effective density of marker layer through bulk and surface roughness regions.

### Surfaces with a Single Peak in the Power Spectrum

Markers that needed a single (i.e. very dominant) peak in the power spectrum were produced using a FTS where the tool motion was coupled to the spindle rotational motion.

This allowed a set of sine waves to be produced on the marker band in the angular direction. This concept is illustrated in Figure 8. The number of sine waves per cylinder ranged from 8 to 28 with amplitudes that ranged from 1.0  $\mu\text{m}$  to 3.0  $\mu\text{m}$ . A conventional diamond tool could be used to machine these features.

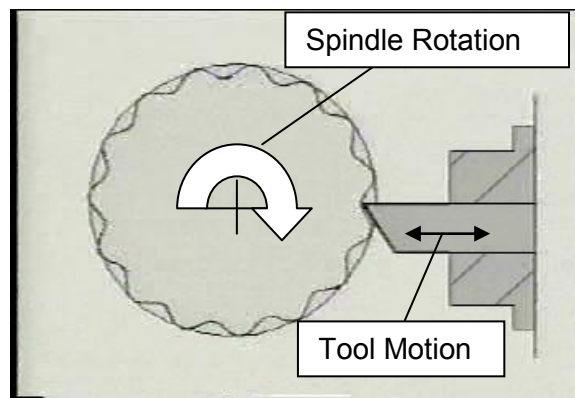


FIGURE 8. Illustration of using FTS to generate sine waves on the exterior of a marker layer.

Measurement of the sine waves was performed while the marker layer cylinder was on the ultra-precision lathe. To do this an air-bearing linear variable differential transformer (LVDT) was mounted to the opposite side of the cylinder from the FTS. The probe to measure the sine waves was a 100  $\mu\text{m}$  diameter sphere that was glued to a 100  $\mu\text{m}$  diameter boron-carbon wire. As the spindle rotated at one revolution per minute the voltage output from the LVDT was recorded by a digital oscilloscope. This digital data was loaded onto a computer for analysis. All of the sine waves were within 100 nm of the nominal shape.

### **JOINT SURFACES**

Since compression of the fusion fuel occurs by accelerating the capsule material toward the capsule center, density variations in the capsule material can cause an unsymmetrical compression to occur. This lack of symmetry can significantly reduce the fusion energy.

Fusion capsules are often made from two hemispheres that are joined together. The discussion above showed that the effective density of a material goes from full density to zero density through the surface roughness region. Therefore, at joints, where two surfaces come together, there will be a density gradient induced by the roughness of the two surfaces.

The reduction in density at the joint can be clearly seen in x-radiographs of fusion capsules. It was decided to investigate finding a way to predict the amount of density gradient that would be produced at a joint composed of surfaces with specific roughness values.

### **Simulation of Machined Surface**

Since the capsules and their joints are machined on a lathe, a mathematical simulation was produced to help gain an understanding of the surface geometry generated by a lathe and how to represent the interface of two surfaces. The simulation represented the surface profile as the intersection of a series of circles (that represented the tool radius) whose centers were separated laterally by one feed distance with randomness introduced for the vertical center position. The radius of the circles was equal to the tool radius. To best simulate an actual surface, the randomness varied about a weighted average of the initial tool position and the center position of the previous pass. A short portion of a simulated surface is shown in Figure 9. The circular portions can be clearly seen; however, the arcs are distorted by axes scales.

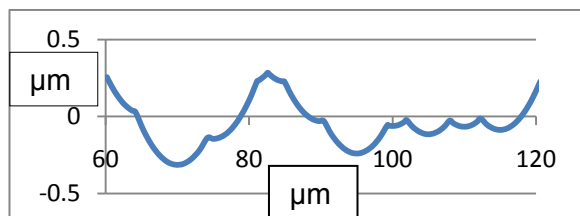


FIGURE 9. Portion of a simulate surface.

### **Bearing Area Ratio for Joints**

The simulation has been useful for helping to understand both the surface geometry and how it is generated. It has also been helpful in confirming that the Bearing Area Ratio plot, which is a plot of density vs. height, can be used to get a reasonable estimate of the density variation through a joint. The problem occurs in knowing how to match the surfaces. Since the surfaces are statistical in nature, the surfaces have to be mated statistically. The most likely height where the peaks of one surface will touch the mating surface is at the mean surface height. By setting the peak of the Bearing Area Ratio plot of one joint surface at this height for the mating surface (as shown in Figure 10) and then summing the effective densities for both surfaces a plot of the density variation across a

joint can be made. A plot for a simulated joint is shown in Figure 11.

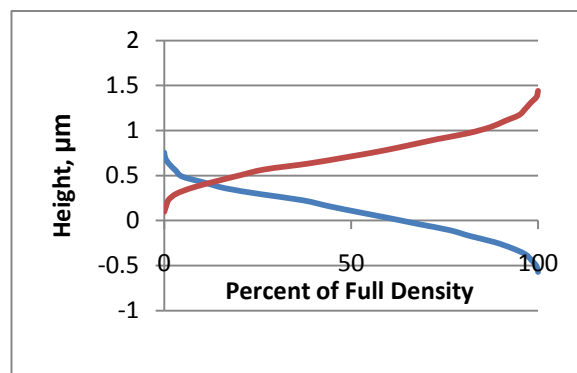


FIGURE 10. Bearing Area Ratio plots for two surfaces in a joint. The peak of one surface is at the mean height of the mating surface.

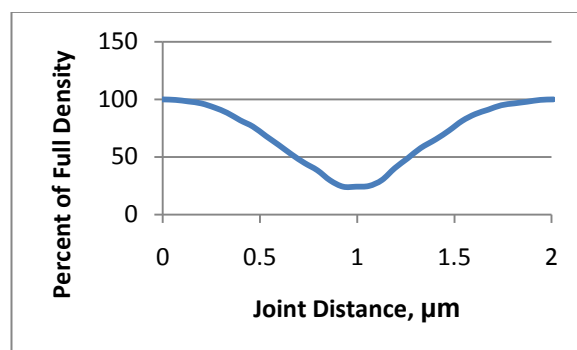


FIGURE 11. Plot of density variation across joint.

The plot in Figure 11 shows that the joint region is 2  $\mu\text{m}$  thick and that it reaches a minimum of 20 % of full density midway through the joint.

### **FUTURE WORK**

The experimental investigations into understanding hydrodynamic instabilities are a continuing effort. Engineered surfaces with specific power spectra will likely need to be produced in the future. We have demonstrated that specific surfaces can be produced, so we have confidence that what will be required in the future can also be produced. (Although there are always some challenges in making the surfaces, we have the technology and methodology to allow us to proceed in the development required.)

Investigations into understanding the density variation at joints will continue. Experimental verification of the density profile will be

attempted using x-radiography. It is planned to extend this work into mating surfaces of plastic and aerogel foams.

## **CONCLUSION**

It has been demonstrated that engineered surfaces with specific power spectra over specified spatial frequencies can be produced. Investigations into effective density variations across joints have begun. The work is primarily theoretical at this time, but measurements of the joint density profile should occur in the future. We are planning to extend the joint work into mating foam surfaces.

## **ACKNOWLEDGEMENTS**

The authors greatly appreciate the support given for this work by the Department of Energy under contract DE-AC52-06NA25396.

## **REFERENCES**

- [1] Brouillette M. The Richtmyer-Meshkov Instability. Annual Review of Fluid Mechanics. 2002; 455.
- [2] Barnes C. Observation of Mix in a Compressible Plasma in a Convergent Cylindrical Geometry. Physics of Plasmas. 1998; 6: 1690.
- [3] Nobile A. Recent Developments in Fabrication of Direct Drive Cylinder Targets for Hydrodynamics Experiments at the Omega Laser. Fusion Science and Technology. 2004; 45: 95-106.
- [4] Balkey M. Production and Metrology of Cylindrical Inertial Confinement Fusion Targets with Sinusoidal Perturbations. Fusion Science and Technology. 2004; 45: 107-112.
- [5] Jared B, Dow T. Precision Engineering Center Annual Report, North Carolina State University. Raleigh, NC. 1996; 123.



# CHARACTERIZING RADII ON THE TIPS OF BIOPSY NEEDLES

Matthew A. Gleason<sup>1</sup>, Christopher A. Brown<sup>1</sup>

Jason Z. Moore<sup>2</sup>, Altert J. Shih<sup>2</sup>

<sup>1</sup> Worcester Polytechnic Institute, Worcester, Massachusetts

<sup>2</sup> University of Michigan, Ann Arbor, Michigan

The objective of this work is to investigate methods for characterizing the radius across the wall of the hollow cylinder, or tube, which forms the tip of needles used for biopsy. This is important because it could influence the force of insertion and quality of the tissue recovered in the biopsy. Furthermore the radii on the walls of the tube could be used to increase the sophistication of the modeling of the tissue behavior during the insertion of the needle. The current models are built on chip formation dynamics using chip flow approximations from geometry of the angle at which the tube is cut to produce the biopsy needle (Moore et al. 2010). Direct measurement of cutting edges has presented a challenge historically, due to the steep slopes adjacent to the edge of interest. This challenge still exists, but is being addressed by recent developments in surface metrology.

This paper examines some of the practical challenges of measuring the edges of cut cylinder, including fixturing. This paper also examines the complexity of determining the radii along a profile. Several approaches are used. One involves determining a profile to analyze, individual profiles versus averaging the profiles over some part of the tip of the cylinder. Another uses a polynomial fit to determine the radii,  $r$ , as a function of position using calculus. And another estimates the radius from three points lying on a circle.

The measurements of the tip are made using a scanning laser confocal microscope. The measurement region encompasses a portion of the cut at the tip of the tube. The cut is oblique. At the tip of the tube there is a larger radius as the cut intersects the interior of the

tube and a smaller radius where the cut intersects the outside of the tube. Across the thickness of the tube the radii are generally large.

Radius is one of the geometric properties of a surface that varies with the scale of observation or calculation. The interactions that determine the performance, like the insertion force or the quality of the tissue in the biopsy, can be sensitive to certain scale ranges (Berglund et al. 2010 a&b). Similarly manufacturing processes could be tuned to influence certain scales preferentially in order to produce surfaces with the desired geometric characteristics in the scale ranges that influence the interactions which control the performance.

## REFERENCES

- [1.] J. Berglund, C. Agunwamba, B. Powers, C. A. Brown, B.-G. Rosén (2010a) On Discovering Relevant Scales in Surface Roughness Measurement-An Evaluation of a Band-Pass Method, *Scanning* 32 244-249.
- [2.] J. Berglund, C.A. Brown, B.-G. Rosen, N. Bay (2010b) Milled Die Steel Surface Roughness Correlation with Steel Sheet Friction, *CIRP Annals Manufacturing Technology* 59/1 577-580.
- [3.] J.Z. Moore, Q. Zhang, C.S. McGill, P.W. McLaughlin, H. Zheng, A.J. Shih (2010) "Cutting Edge Rake and Inclination Angles Modeling for Plane Needles," *ASME Journal of Manufacturing Science and Engineering*, Vol. 132, pp. 051005-1-8.

# NEW MEASUREMENT TECHNIQUE IN RESEARCH AND DEVELOPMENT OF BIORESORBABLE IMPLANT MATERIAL

Stefan Scherer<sup>1</sup>, Stefan Fischerauer<sup>2</sup>, and Annelie Weinberg<sup>2</sup>

<sup>1</sup>CEO, Alicona

Grambach/Graz, Austria

<sup>2</sup>Department of Pediatric Surgery Med University  
Graz, Austria

## ABSTRACT

In this paper an optical 3D surface measurement technology is presented that is capable of measuring the topological characteristics of bioresorbable implants. This information can be used to get insights into the dissolution process. The used 3D instrument is based on the Focus-Variation principle which is able to measure even rough and sculptured surfaces at high resolutions up to 10nm. Three different materials were examined before they have been implanted and various roughness parameters have been measured in order to compare the topological characteristics of the different materials.

## INTRODUCTION

The conventional treatment of fractures in children often include the usage of steel or titanium implants. It is obvious that after the healing process these implants have to be removed at a second surgery in a child. Recent developments now focus on implants that are degradable or bioresorbable in the bone after the healing of the fracture.

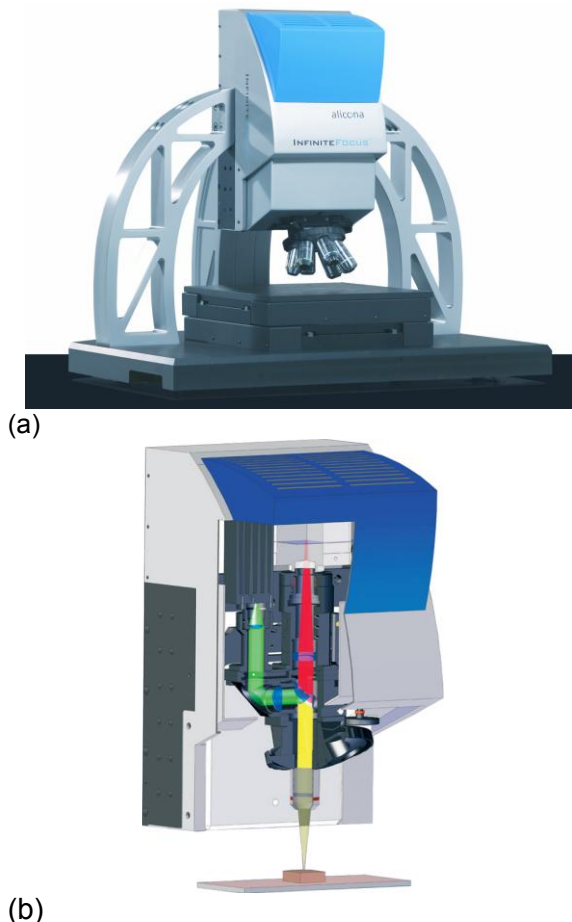
Promising results are achieved with materials on polymer and magnesium basis, however especially if applied to children these materials can likely cause undesired inflammations. Also most research and data is available for adults where a second, avoidable surgery is not always necessary would be especially desirable for children in orthopedic trauma surgery. The key question to answer in the research and development of bioresorbable implant material is to easily, accurately and repeatably quantify even the smallest amount of dissolution of the material.

In this paper an optical 3D surface measurement technology is presented that is capable of measuring the dissolution of the examined material in the micro- and nano level. Implants of the material to be evaluated are implanted into

rats who carry the material for a certain period. Within defined time periods the implants are removed and the dissolution of the material is quantified.

## SURFACE ROUGHNESS MEASUREMENT

The applied measurement technology is called Focus-Variation [1] and provides a vertical resolution of up to 10nm. Focus-Variation combines the small depth of focus of an optical system with vertical scanning to provide topographical and color information from the variation of focus. In the following, the operating principle is demonstrated using the optical 3D measurement device InfiniteFocus (Fig. 1a), schematically shown in Fig. 1b. The main component of the system is a precision optic containing various lens systems that can be equipped with different objectives, allowing measurements with different resolution. With a beam splitting mirror, light emerging from a white light source is inserted into the optical path of the system and focused onto the specimen via the objective. Depending on the topography of the specimen, the light is reflected into several directions as soon as it hits the specimen via the objective. All rays emerging from the specimen and hitting the objective lens are bundled in the optics and gathered by a light sensitive sensor behind the beam splitting mirror. Due to the small depth of field of the optics only small regions of the object are sharply imaged. To perform a complete detection of the surface with full depth of field, the precision optic is moved vertically along the optical axis while continuously capturing data from the surface. This means that each region of the object is sharply focused. Algorithms convert the acquired sensor data into 3D information and a true color image with full depth of field. This is achieved by analyzing the variation of focus along the vertical axis.



**FIGURE 1.** (a) IFM G4 laboratory system (b) schematic visualization of the focus-variation technology. The small depth of focus of the optical system is used to extract depth information with registered true color.

The vertical scan range depends on the working distance of the objective and ranges from 3.2 to 22mm. In contrast to conventional techniques, the vertical resolution is achieved regardless the scan height leading to a vertical resolution dynamic of 1: 430000.

The XY range is determined by the used objective and typically ranges from 0.14 x 0.1mm to 5 x 4 mm for a single measurement. By using special algorithms and a motorized XY stage the XY range can be exceeded up to 100 x 100mm.

In contrast to other optical techniques that are limited to coaxial illumination, the max. measurable slope angle is not only dependent on the numerical aperture of the objective. Focus-Variation can be used with a large range of different illumination sources (such as a ring light) which allows the measurement of slope

angles exceeding 80°. This is especially necessary for roughness measurements on rather craggy surfaces as for typically used materials (e.g. material 1 shown in the result section). Basically, Focus-Variation is applicable to surfaces with a large range of different optical reflectance values. As the optical technique is very flexible in terms of using light, typical limitations such as measuring surfaces with strongly varying reflection properties even within the same field of view can be avoided. Specimen can vary from shiny to diffuse reflecting, from homogeneous to compound material and from smooth to rough surface properties.

In addition to the scanned height data, Focus-Variation also delivers a color image with full depth of field which is registered to the 3D points. This provides an optical color image which eases measurements as far as the identification and localization of measurement fields or distinctive surface features are concerned. The visual correlation between the optical color image of the specimens' surface and its depth information are often linked to each other and are therefore an essential aspect of meaningful 3D measurement.

Focus-Variation is used to perform high resolution 3D surface measurement for industrial quality assurance as well as research and development activities. Key applications are surface analysis and characterization in e.g. cutting tool industry, precision manufacturing, automotive industry, all kinds of materials science, corrosion and tribology, electronics, medical device development or paper and print industry [2].

## RESULTS

In this section we provide 3D measurement results for three different materials before they have been implanted. These 3D measurements serve a dual purpose. In the first place they can be used to compare the topological characteristic of the different materials to each other. In the second place they act as reference measurements for the comparison with implants after they have been implanted for a certain time. Since currently no data on already implanted material are available we focus in the following on the comparison of the different materials.

In order to compare different materials the surface roughness parameters have been measured. Since the implants have a cylindrical

form it is necessary to remove this form in order to achieve reasonable roughness measurement results.

In total the procedure for calculating the roughness parameters is as follows:

1. 3D measurement using InfiniteFocus
2. Removing the cylindrical form (Fig. 2)
3. Waviness filtering using a cut-off frequency  $L_c$  of  $200\mu\text{m}$
4. Calculation of roughness parameters conform to ISO 25178-2 [3]

The area based roughness measurement has been chosen because it delivers more repeatable and significant results than traditional profile roughness measurements.

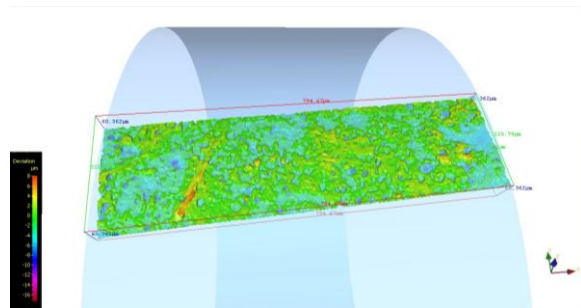


FIGURE 2. Process of removing the cylindrical form (visualization of material 1) The color visualized the deviation to the geometric primitive of a cylinder.

In the following the 3D-measurement results for the three materials are presented. Followed by the comparison of the roughness parameters at the end of this section.

#### **Material 1 (Magox)**

Magox is a LV1 alloy. The surface has been treated with the plasma electrolytic oxidation. This material has a rather craggy surface. Figure 3 shows the measured datasets of material 1. Figure 4 shows the dataset where the cylindrical form has been removed and the roughness has been filtered with a  $L_c$  of  $200\mu\text{m}$ .

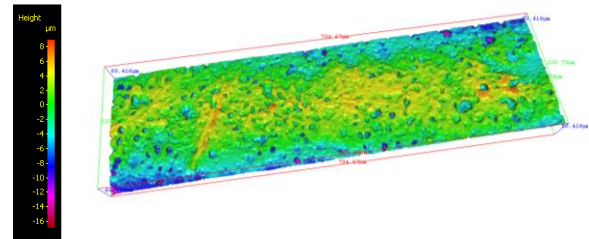
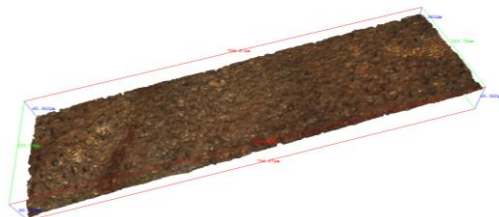


FIGURE 3. 3D measurement of material 1 displayed in true and in pseudo colors

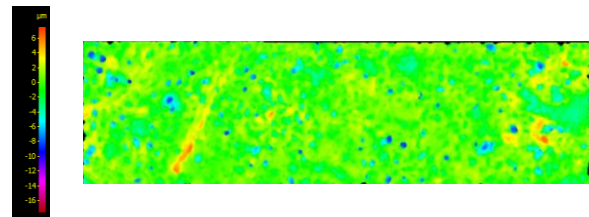


FIGURE 4. Filtered roughness dataset of material 1. Cylindrical form and roughness with a  $L_c$  of  $200\mu\text{m}$  has been filtered out.

#### **Material 2 (WZ21)**

The second material is crystalline magnesium alloy with the chemical composition of:

- Mg
- 1% Zn
- 0,25% Ca
- 0,15% Mn
- 2% Yttrium

This material has a directed surface structure. Figure 5 shows the measured dataset whereas Figure 6 visualizes the filtered dataset.

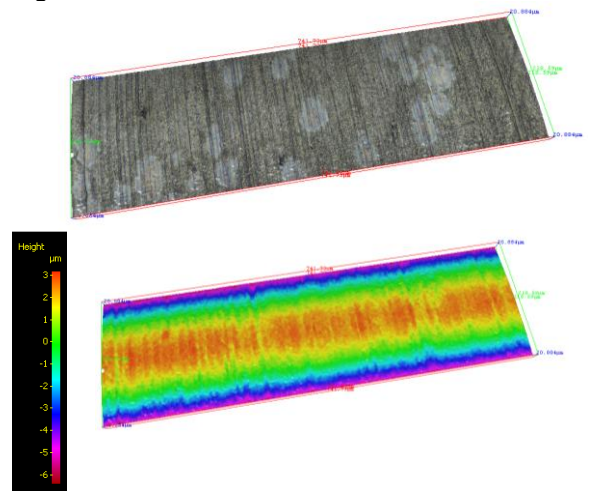


FIGURE 5. 3D measurement of material 2 displayed in true and in pseudo colors



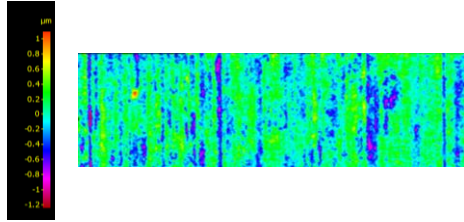


FIGURE 6. The cylindrical form has been removed from the original dataset of material 2. After this a roughness filter with the Lc of 200 $\mu$ m has been applied.

### Material 3 (LU1)

The third materials is crystalline magnesium alloy with the chemical composition of:

- Mg
- 5% Zn
- 0,25% Ca
- 0,15%Mn

This material is similar to material 2. But one big difference is the surface waviness. As it can be seen when comparing Figure 6 and Figure 8 the roughness dataset of Figure 8 includes significantly more surface waviness after being filtered with the same Lc.

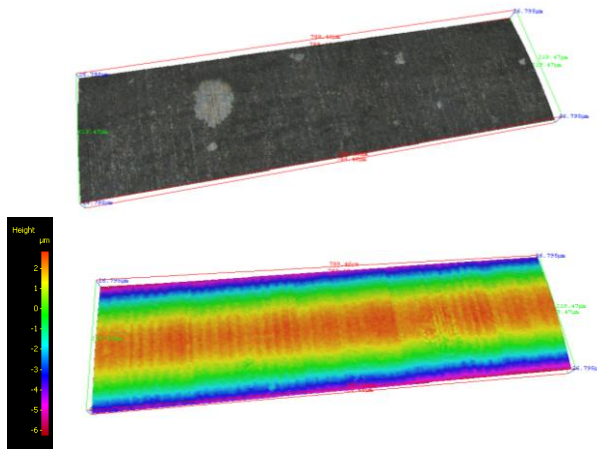


FIGURE 7. 3D measurement of material 3 displayed in true and in pseudo colors

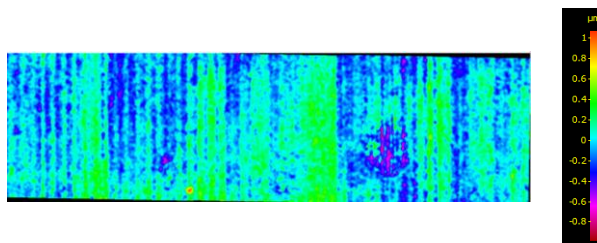


FIGURE 8. The cylindrical form has been removed from the original dataset of material 3 in order to achieve a significant roughness measurement

### Comparison of Roughness Values

When comparing the roughness values in table 1 it can be seen that material 1 has a much rougher surface than the materials 2 and 3. When comparing the filtered roughness datasets material 3 still shows waviness after being filtered with a Lc of 200 $\mu$ m whereas the similar material 2 does not show this waviness.

TABLE 3. A selection of area based roughness parameters of material 1 to 3 – filtered with the Lc of 200 $\mu$ m

| Parameter | Material 1    | Material 2   | Material 3   |
|-----------|---------------|--------------|--------------|
| Sa        | 1.32 $\mu$ m  | 0.19 $\mu$ m | 0.12 $\mu$ m |
| Sq        | 1.85 $\mu$ m  | 0.25 $\mu$ m | 0.15 $\mu$ m |
| Sz        | 25.12 $\mu$ m | 2.33 $\mu$ m | 1.87 $\mu$ m |

### CONCLUSIONS

We have shown how bioresorbable implants can be measured using an optical instrument based on the Focus-Variation principle and how they can be compared using area based roughness parameters. The measurements have shown that one of the materials was by a factor of 10 rougher than the other two and consisted of a very random structure compared to the other two with rather a directed structure. Although the other two materials did not show a significant difference in roughness parameters the measured 3D datasets provided a clear difference with respect to frequencies at special wave lengths.

The next steps in this research are to evaluate the materials after a certain implant time. For the next measurements we plan not only to measure the surface characteristics but also to measure the full form of the implant before and after being implanted. This would help to gain additional information about the dissolution process of the material.

### REFERENCES

- [1] ISO 25178-6: Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 6: Classification of methods for measuring surface texture, Draft.
- [2] Scherer, S.: Focus-Variation for optical 3D measurement in the micro- and nano-range, Handbuch zur Industriellen

Bildverarbeitung: Qualitätssicherung in der Praxis, Fraunhofer IRB Verlag, 2007.

- [3] ISO/TS 25178-2 - Draft, Geometrical product specifications (GPS) -- Surface texture: Areal -- Part 2: Terms, definitions and surface texture parameters.

# METROLOGICAL CHARACTERIZATION OF REPTILIAN SKIN FOR GREEN TRIBO SURFACES

**Hisham A. Abdel-Aal; Mohamad El Mansori**  
**Arts et Metiers Paris Tech**  
**Châlons-en-Champagne Cedex 51996, France**

Optimization of surface constructs reflect on the longevity, integrity and energy consumption profiles of any rubbing assembly. Development of rubbing surfaces of predictable tribological response where surface features, profile and texture, are integral to their function is therefore desirable. Obtaining a predetermined tribological response, depends on controlling the structure of the rubbing interface. In seeking inspirations for deterministic structuring of surfaces, many engineers turn toward natural systems (Bio-systems) in an attempt to formulate viable design rules for deterministic surface constructs.

Squamate Reptiles (SR) present diverse examples where surface structuring, and modifications through submicron and nano-scale features, achieve frictional regulation. Squamata comprises two large clades, Iguania (about 1,230 known species) and Scleroglossa (about 6,000 known species), 3,100 of which are traditionally referred to as “lizards,” and the remaining 2,900 species as “snakes”. Squamates are found almost everywhere on earth except where factors that limit their survivability are present. Their ecological diversity, and thereby their diverse habitat, presents a broad range of tribological environments that require specific tribological functional practices and surface design features. Squamates, therefore offer a great resource that can be mined for viable surface design inspirations.

To deduce design rules there is a need to quantify the relation between micro-structure, topology and strength of the bio-surface; exploring the link between macro and micro texture, and finally devising working formulae that describe (and potentially predict) load carrying capacity during locomotion in relation to geometrical configuration at both the micro and the macro scale.

This work deals with the first requirement: quantifying the geometrical build up of the surface in terms of Manufacturing Standardized Parameters (MSP). We utilize multi-scale surface characterization to study surface design features of the Python Regius (Ball Python). We show that the ventral scales of the reptile are hierarchical structured surfaces. We further show that such surfaces are optimized for all the influential parameters that affect the tribological response of deterministic surface constructs.





# Authors Index

Abdel-Aal, Hisham A. . . . . 167\*

Arenhart, F. A. . . . . 68

Arneson, David A. . . . . 74

Ascione, Rocco . . . . . 49

Avila, Miguel . . . . . 127

Bambrick, Scott T. . . . . 34, 87\*

Beutler, Andreas . . . . . 133

Biermann, Dirk . . . . . 55, 120

Bosse, Harald . . . . . 68

Boudreau, Brian D. . . . . 82

Bowes, Kevin . . . . . 137

Brecher, Christian . . . . . 117

Brinksmeier, Ekkard . . . . . 29

Brown, Christopher A. . . . . 161\*

Bryant, Loren A. . . . . 91

Burge, James H. . . . . 43

Buß, Christian . . . . . 117

Butel, G. . . . . 43

Cannarozzo, Vince . . . . . 87\*

Cannistra, Aaron T. . . . . 10\*

Cannon, Andrew H. . . . . 147, 150

Carrigan, Keith. . . . . \*\*

Choi, Soochang . . . . . 59

Clemens, Jürgen. . . . . 117

Davies, Angela D. . . . . 137

Davies, Matthew A. . . . . 10\*, 105

Davis, Gregg E. . . . . 111

Day, Robert D. . . . . 156

de C. Porath, M. . . . . 68

DeFisher, Scott . . . . . 34

Dominguez, Margaret. . . . . 43

Donatelli, G. . . . . 68

Dow, Thomas A. . . . . 13, 38

Dubey, Manjesh . . . . . 150

Dutterer, Brian S. . . . . 10\*, 105

Eberhardt, Ramona. . . . . 19

El Mansori, Mohamad . . . . . 167\*

Fess, Edward . . . . . 87\*

Fischerauer, Stefan . . . . . 162

Fuerschbach, Kyle H. . . . . 3

Garrard, Kenneth P. . . . . 13, 38

Gebhardt, Andreas . . . . . 19

Giusca, Claudiu . . . . . 126\*

Gläbe, Ralf. . . . . 29

Gleason, Matthew A. . . . . 161\*

Härtig, Frank . . . . . 68

Hatch, Douglas J. . . . . 156

Hedges, Alan R. . . . . 111

Hense, Rouven . . . . . 55

Hirano, Minoru . . . . . 24

Howard, Joseph M. . . . . 8

Huber, Justin. . . . . 79

Hull, Tony. . . . . \*\*

Hulseman, Ralph. . . . . 150

Ishida, Tohru . . . . . 24

Ismail, Mohd Fauzi . . . . . 63

Isobe, Hiromi . . . . . 63

Jusko, Otto E. . . . . 68

Kim, Kyunghan . . . . . \*\*

King, William P. . . . . 147

Knapp, Byron R. . . . . 74

Kniel, Karin . . . . . 68

Krebs, Eugen. . . . . 120

Lambropoulos, Theodore. . . . . 34

Leach, Richard K. . . . . 126\*

Lee, Deug Woo . . . . . 59

Lee, Jaehoon . . . . . \*\*

Lee, Sang-min . . . . . 59

Li, Lei. . . . . 19

Li, Zhichao. . . . . 91

Liebers, Melvin J. . . . . 74

Lineberger, Jennifer Lynn . . . . . 105

Lu, Hong . . . . . 59

Lu, Sheng-Huei . . . . . 43

Luttrell, Dan E. . . . . 143

Maguire, March . . . . . 147

Marsh, Eric R. . . . . 74

Mears, Laine . . . . . 150

Moore, Jason Z. . . . . 161\*

Morgan, Christopher J . . . . . 79

Moroni, Giovanni . . . . . 49

Morse, Edward P. . . . . 137

Mullany, Brigid A. . . . . 137

Nakamoto, Keiichi. . . . . 24

\*\* No abstract available

\* No extended abstract available at press time

|                                |            |
|--------------------------------|------------|
| Neugebauer, Reimund . . . . .  | 127        |
| Odendahl, Sven . . . . .       | 55         |
| Oss, Daniel D. . . . .         | 74         |
| Park, Jong-Kweon . . . . .     | 59, 88, ** |
| Park, Won Hyun . . . . .       | 43         |
| Parks, Robert E. . . . .       | 43         |
| Petrò, Stefano . . . . .       | 49         |
| Plummer, William T. . . . .    | 11         |
| Raja, Jayaraman . . . . .      | 82, 101    |
| Ramasamy, Suresh K. . . . .    | 82         |
| Rausch, Sascha . . . . .       | 55         |
| Risse, Stefan . . . . .        | 19         |
| Rivera, Gerald . . . . .       | 156        |
| Roblee, Jeffrey W. . . . .     | 111        |
| Rolland, Jannick P. . . . .    | 3          |
| Romano, Daniele . . . . .      | 49         |
| Scheiding, Sebastian . . . . . | 19         |
| Scherer, Stefan . . . . .      | 162        |
| Schlenker, Juliane . . . . .   | 120        |
| Schmidt, Torsten . . . . .     | 127        |
| Schönemann, Lars . . . . .     | 29         |
| Schubert, Andreas . . . . .    | 127        |
| Shafir, Shai N. . . . .        | 34, 87*    |
| Shih, Albert J. . . . .        | 161*       |
| Smilie, Paul J. . . . .        | 105        |
| Sohn, Alex. . . . .            | 13, 38     |
| Sohn, Hyonkee . . . . .        | 88         |
| Stanco, Matthew R. . . . .     | 91         |
| Steiner, Markus . . . . .      | 55         |
| Stephens, Scott . . . . .      | 79         |
| Su, Peng . . . . .             | 43         |
| Su, Tianquan . . . . .         | 43         |
| Suh, Jeong . . . . .           | 88, **     |
| Suleski, Thomas J. . . . .     | 10*, 105   |
| Surmann, Tobias . . . . .      | 55         |
| Sylla, David . . . . .         | 127        |
| Takeuchi, Yoshimi . . . . .    | 24         |
| Tanaka, Hidetake . . . . .     | 96         |
| Thompson, Kevin P. . . . .     | 3          |
| Tierson, Jayson . . . . .      | 87*        |
| Tünnermann, Andreas . . . . .  | 19         |
| Vallance, R. Ryan . . . . .    | 74         |
| Vergara, Jesse . . . . .       | 91         |

|                              |        |
|------------------------------|--------|
| Verma, Ritwik . . . . .      | 101    |
| Walker, Nicholas . . . . .   | **     |
| Wang, Lirong . . . . .       | 43     |
| Wang, Yuhao . . . . .        | 43     |
| Weinberg, Annelie . . . . .  | 162    |
| Weingärtner, Simon . . . . . | 29     |
| Wenzel, Christian . . . . .  | 117    |
| Yamamoto, Shingo . . . . .   | 24     |
| Yanagi, Kazuhisa . . . . .   | 63, 96 |
| Yi, Allen Y. . . . .         | 19     |
| Zhou, Ping . . . . .         | 43     |
| Zhu, G. . . . .              | 43     |
| Zobrist, Thomas . . . . .    | 43     |

\*\* No abstract available

\* No extended abstract available at press time

# ASPE 2011 Sustaining Corporate Sponsors



**3M Company**  
St. Paul, MN 55144  
Phone: (651) 737-3790  
www.mmm.com



**ADCOLE Corporation**  
669 Forest Street  
Marlborough, MA 01752  
Phone: (508) 485-9100  
Fax: (508) 481-6142  
www.adcole.com



**Aerotech, Inc.**  
101 Zeta Drive  
Pittsburgh, PA 15238-2897  
Phone: (412) 963-7470  
Fax: (412) 963-7459  
www.aerotech.com



**AMETEK-Precitech, Inc.**  
44 Blackbrook Road  
Keene, NH 03431  
Phone: (603) 357-2511  
Fax: (603) 358-6174  
www.precitech.com



**Bruker Nano Surfaces Business**  
2650 East Elvira Road  
Tucson, AZ 85706-7123  
Phone: (520) 741-1044  
www.bruker-nano.com



**Chardon Tool**  
115 Parker Court  
Chardon, OH 44024  
Phone: (440) 286-6440  
Fax: (440) 286-7165  
www.ChardonTool.com



**Contour Fine Tooling, Inc.**  
143 Jaffrey Road  
Marlborough, NH 03455  
Phone: (603) 876-4908  
www.contour-diamonds.com



**Equilibria**  
472 Amherst Street  
Unit 25  
Nashua, NH 03063  
Phone: (603) 880-7722  
www.eqlib.com



**K & Y Diamond**  
2645 Diab St. Laurent  
Quebec H4S 1E7  
CANADA  
Phone: (514) 333-5606  
Fax: (514) 339-5493  
www.kydiamond.ca



**Lion Precision**  
563 Shoreview Park Road  
St. Paul, MN 55126-7014  
Phone: (651) 484-6544  
Fax: (651) 484-6824  
www.lionprecision.com



**Makino**  
7680 Innovation Way  
Mason, OH 45040  
Phone: (513) 573-7200  
Fax: (513) 573-7360  
www.makino.com



**Mitutoyo America Corporation**  
945 Corporate Boulevard  
Aurora, IL 60504-9102  
Phone: (630) 723-3619  
Fax: (630) 978-6471  
www.mitutoyo.com



**Moore Nanotechnology Systems LLC**  
426A Winchester Street  
Keene, NH 03431-0605  
Phone: (603) 352-3030  
www.nanotechsys.com



**Newport Corporation**  
1791 Deere Avenue  
Irvine, CA 92606  
Phone: (949) 863-3144  
Fax: (949) 253-1667  
www.newport.com



**PI (Physik Instrumente) L.P.**  
16 Albert Street  
Auburn, MA 01501  
Phone: (508) 832-3456  
www.physikinstrumente.com



**Professional Instruments Company**  
7800 Powell Road  
Hopkins, MN 55343  
Phone: (952) 933-1222  
Fax: (952) 933-3315  
www.airbearings.com



**Specialty Components, Inc.**  
14 Village Lane  
Wallingford, CT 06492  
Phone: (203) 284-9112  
Fax: (203) 672-0371  
www.specialtycomponents.com



**Trust Automation, Inc.**  
143 Suburban Road  
San Luis Obispo, CA 93401  
Phone: (805) 544-0761  
Fax: (805) 544-4621  
www.trustautomation.com



**Zygo Corporation**  
Laurel Brook Road  
Middlefield, CT 06455-0448  
Phone: (860) 347-8506  
Fax: (860) 347-8372  
Toll-free: (800) ZYGO-NOW  
www.zygo.com

# ASPE 2011 Corporate Sponsors

**Center for Precision Metrology  
University of North Carolina at Charlotte**

9201 University Blvd.  
Charlotte, NC 28223  
Phone: (704)-687-8499  
[www.cmp.uncc.edu](http://www.cmp.uncc.edu)

**euspen Ltd.**

Building 70  
Cranfield University Campus  
Bedford, MK43 0AL, United Kingdom  
Phone: +44-(0)1234-754024  
[www.euspen.org](http://www.euspen.org)

**Corning Inc.**

Science & Technology Division  
HP-ME-03-055  
Corning, NY 14831  
Phone: (607) 974-3842  
[www.corning.com](http://www.corning.com)

**nanoPrecision Products, Inc.**

411-B Coral Circle  
El Segundo, CA 90245  
Phone: (310) 773-3550  
[www.nanoprecisionproducts.com](http://www.nanoprecisionproducts.com)

**Cranfield Precision**

Division of Cinetic Landis Lund, Ltd.  
90 Central Avenue  
Wharley End  
Cranfield, Bedford MK43 0JR  
United Kingdom  
Phone: +44-(0)1234-754023  
[www.cranfieldprecision.com](http://www.cranfieldprecision.com)





**Volume 51**

ISBN 978-1-887706-57-5